Solar Process Heat in the Food Industry –

Methodological Analysis and Design of a Sustainable Process Heat Supply System in a Brewery and a Dairy

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INSTITUTE FOR NEW ENERGY SYSTEMS

Declaration

I declare that the content of this submission is my own work. The contents of the work have not been submitted for any other academic or professional award. I acknowledge that this thesis is submitted according to the conditions laid down in the regulations. Furthermore, I declare that the work was carried out as a part of the course for which I was registered at the De Montfort University, United Kingdom from April 2010 until April 2016. I draw attention to any relevant considerations of rights of third parties.

Abstract

The food industry is a large consumer of industrial energy. A very large portion of this energy is needed in the form of thermal energy at medium to low temperatures. Fossil fuels remain the dominant sources of this energy. This combination provides various possibilities to reduce energy consumption and CO2 emissions with heat recovery, but also with the integration of solar process heat. Energy efficiency must provide the context, or background, of such considerations, and is therefore a very important aspect of them.

It is a complex task to design an efficient heat supply with a variety of energy sources. An analysis of standards for energy audits, guides for energy efficiency and guides for solar process heat integration confirms that complexity. However, no available methodology considers all the necessary steps. These must range from analysis of the existing heat supply to the redesign of an efficient heat supply system. The focus must be on heat sources with waste heat and on solar process heat that might be used to complement the conventional sources.

The design of a process heat system is mainly the task of design engineers in engineering offices. Specific tools and measures are needed to support these experts. However, the companies of the food industry sector employ their own energy engineers for energy issues. These people are actually the decision makers responsible for the configuration of the company energy supply systems, who also possess knowledge of the processes in their industry subsector. The expertise of the energy engineers varies within a broad range and is also connected to their area of responsibility. Therefore, it is important to consider these energy engineers when developing a methodology.

The development of the methodology proposed herein consists first of the configuration of the tools and measures, which were assigned to four elements and functions. Second, the methodology so developed was applied at two companies in cooperation with their energy engineers, in detailed case studies. The feedback from the energy engineers is therefore a main objective and provides a background for evaluation of the usability of the methodology. It

demonstrates the expertise required of the energy engineers, for the application of the tools and measures provided. Moreover, the development and application of the methodology involving real companies demonstrates the necessity of getting feedback from energy engineers. That finding is very important, and has been insufficiently considered in previous guides or methodologies.

It is proposed that further work be aimed at providing additional case studies to extend the use of this methodology to other parts of the food industry.

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Abbreviations

bat	Batch
BW	Brew Water
cf.	compare (Latin: confer)
CH_4	Methane
CHP	Combined Heating and Power
CO_2	Carbon Dioxide
Col	Collector
EEM	Energy Efficiency Measures
EU25	Member-States of the European Union before enlargement in 2007 (EU28 without Bulgaria, Romania and Croatia)
EU28	Member-States of the European Union since enlargement in 2013
GHG	Greenhouse Gas
GWh	Gigawatt hours
hl	Hectolitre (Common Unit for 100 l beer and other drinks)
HEN	Heat Exchanger Network
HRC	Heat Recovery Circuit
hr	Heat Recovery
hrf	Heat Recovery Factor
kg	Kilogram
km	Kilometre
LE	Large Enterprise
LPG	Low Pressure Gas
LGH	Low-grade Heat
MES	Manufacturing Executive System

NAB	Non-Alcoholic Beverage
NH_3	Ammonia (used as refrigerant in chillers)
N_2O	Nitrous Oxide
NTU	Number of Transfer Units
OE	Oil Equivalent
Opar	Operation Parameter
PET	Polyethylenterephthalat
PU	Production Unit
Q_{Prim}	Primary Energy
Q_{Fin}	Final Energy
Q_{Use}	Useful Energy
Q_{los}	Energy Loss
Q_{trans}	Energy Transmission
ROI	Return on Investment
SCE	Specific Collector Earnings
SH	Space Heating
SME	Small and Medium-Sized Enterprise
SPH	Solar Process Heat
ST	Storage
SW	Service Water
HSW	Hot Service Water
TWh	Terawatt hours
tOE	tonnes of Oil Equivalent
UHT	High Temperature Pasteurisation
UF	Utilisation Factor

Symbols

~	Approximately	[-]
Ø	Average Value	[-]
Δ	Difference	[-]
A	Area	[m²]
c_p	Specific Heat Capacity	[J kg^{-1} K^{-1}]
CP	Heat Capacity Flow Rate	[W K^{-1}]
dx	Distance between two nodes	[m]
f_{sol}	Solar Fraction	[%]
k	Heat Transfer Coefficient	[W m^{-2} K^{-1}]
K	Transmitting Capacity	[W K^{-1}]
p	Pressure	[Pa]
Q	Energy	[kWh]
$\dot{q}$	Power	[W]
t	Time	[s]
T	Temperature	[°C]
u	Heat loss	[W m^{-2} K^{-1}]
u_1	Linear heat loss coefficient	[W m^{-2} K^{-1}]
u_2	Quadratic heat loss coefficient	[W m^{-2} K^{-2}]
v	Speed	[m s^{-1}]

Subscripts

abs	Absolute
amb	Ambient
back	Backup
ba	Balance Area
beer	Beer
by	Bypass
ca	Compressed Air
cb	Cold batch
cc	Charging Circuit
ch	Chiller
col	Collector
con	Consumer
conv	Conventional
CO2	Carbon Dioxide
CO2e	CO_2 Equivalent
def	Defined
dist	Distribution
dur	Duration
evap	Evaporation
el	Electrical

fos	Fossil Energy
he	Heat Exchanger
hb	Hot batch
hr	Heat Recovery
loss	Losses
med	Medium
min	Minimal
n	Node
pip	Piping
proc	Process
sc	Solar Circuit
sky	Sky
sol	Solar
sour	Source
st	Storage
supp	Supply
tar	Target
th	Thermal
wind	Wind

1 Introduction

1.1 Background

Non-renewable energy sources supply most of the energy worldwide (Figure 1.1). This consumption of mainly fossil primary energy depletes resources and reduces their availability for future generations. Furthermore, the depletion of fossil resources is mainly responsible for the anthropogenic greenhouse effect from CO_2 emissions. Consequently, sustainable technologies are necessary. The industry sector causes almost 30% of the CO_2 emissions in Europe (EUROSTAT, 2012). In this case, the energy demand by industry provides various possibilities to reduce fossil fuel consumption and CO_2-emissions. Energy efficient production and renewable energy sources help reduce fossil fuel consumption and simultaneously support industry in managing energy costs.

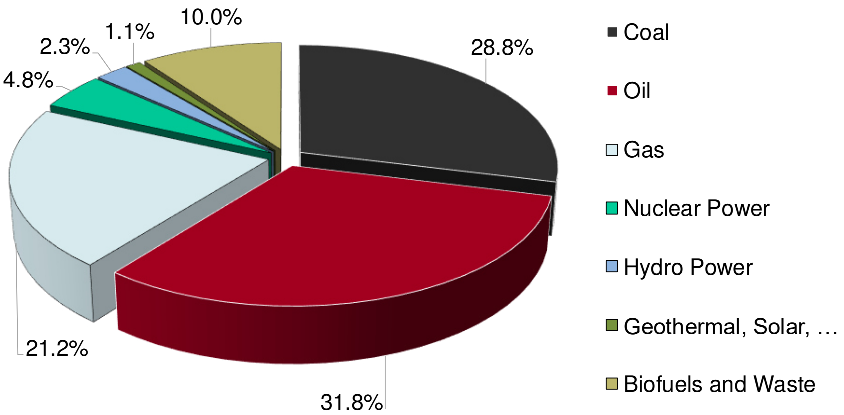

Figure 1.1: Energy Sources of World Primary Energy Consumption 2012 (IEA 2015)

The total world primary energy consumption has grown by an average of 2% each year since 2000. This growth in energy demand is mainly caused by the developing and emerging countries (Brazil, China, India …). In the developed nations, the energy consumption is mainly static. As Figure 1.2 illustrates, this is the same for the EU28 and quite comparable to Germany. Primary energy consumption for these regions has been at nearly the same level for the last ten years. With regard to the objectives of the EU28 and German government concerning reduced future energy consumption, this is very significant.

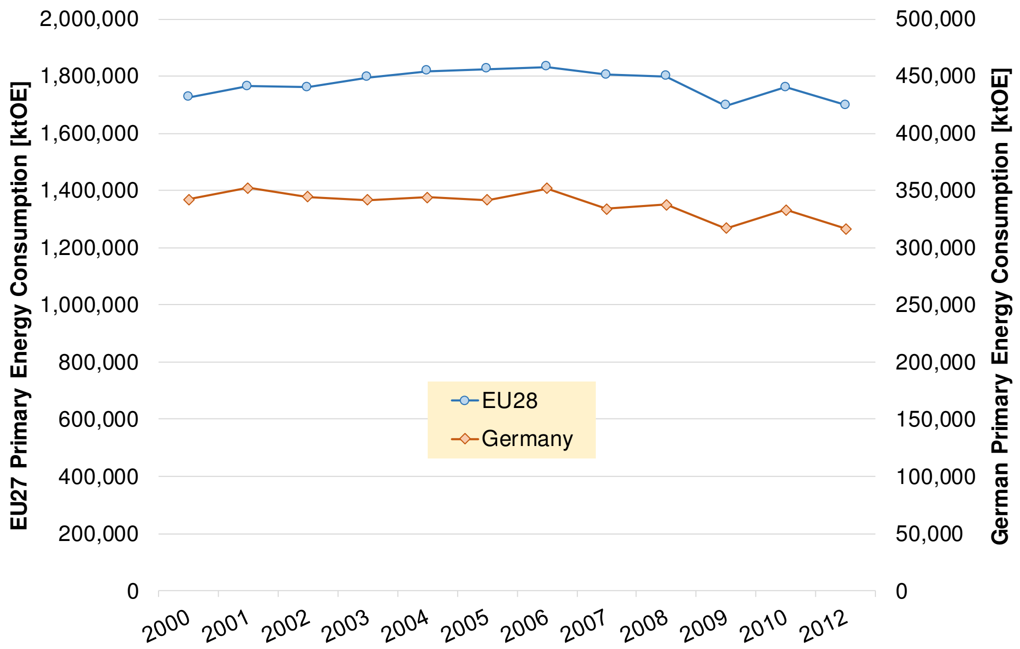

Figure 1.2: Trend of Primary Energy Consumption (cf. EUROSTAT, 2012)

There are three major challenges concerning a sustainable and reliable energy supply to all future energy consumers:

- minimise CO_2 emissions to reduce the greenhouse effect,
- ensure an energy supply affordable to the consumer,
- ensure a reliable energy supply to avoid unbalanced dependency.

To handle the problems connected with fossil energy consumption, the EU28 and the German government set ambitious targets. This means a significant reduction of CO_2 emissions (by 80%) and additional reduction of primary energy use (by 50%) by the year 2050, as compared to 1990. Furthermore, CO_2 emissions and primary energy consumption are also to be reduced by 20% by the year 2020. Renewable energies have to contribute a major part to achieve these goals (cf. Dürrenschmitt, 2012).

As shown in Figure 1.3 the energy consumption described before can be subdivided into the sectors industry, traffic, residential, and others (e.g. service). The

German industry sector consumed about 29% of the final energy demand in 2012, which is also comparable to the EU28 (EUROSTAT, 2012; BMWi, 2012).

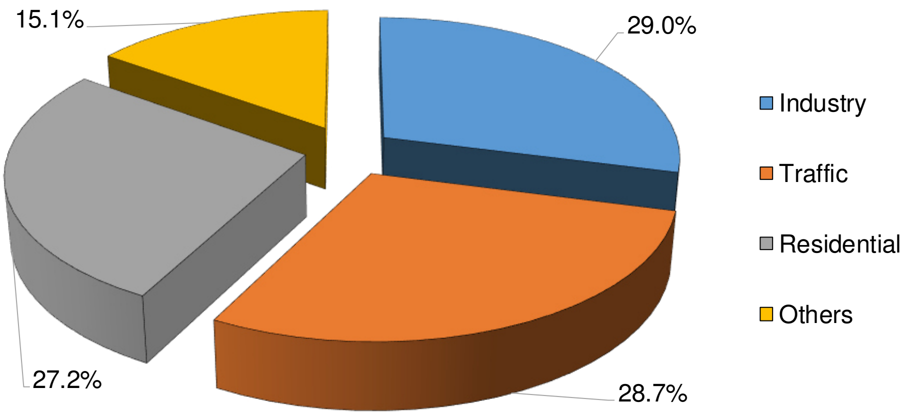

Figure 1.3: Final Energy Demand in Germany 2012 – Consumer Sectors (BMWi, 2014)

It is remarkable that a major part of the industrial energy demand is not for electricity but for thermal energy to supply production processes or space heating. Obviously, this demand for heat reflects all applications and reaches temperatures of more than 1000°C. However, nearly one third of this heat consumption requires temperatures below 200°C and about 20% requires temperatures below 100°C. This is exactly the best application range for waste heat recovery and also for renewable energy sources. Solar-thermal systems today are already able to provide a large proportion of this low-grade heat (Lauterbach, 2012; Aidonis, 2005).

Using state-of-the-art solar-thermal system technologies, supplying heat at temperatures up to 100°C is possible. Various applications and processes for paper manufacturing, chemical products and in the food industry do not exceed this temperature level and provide favourable conditions and huge potential.

1.2 Energy efficient production

Industry aims to combine energy efficient production to handle the requirements for energy consumption and low emissions, with economic efficiency. These, however, do not align in each case. There are several aspects to consider regarding the implementation of energy efficient technologies.

The most important one is the *energy cost* and resulting *economic efficiency* of the investment. Industry evaluates energy costs compared to gross production value. Calls for action are therefore, related to high and increasing energy costs. Competition with other companies and the specific market conditions for the produced goods can intensify this aspect.

Legislation – national or international – is a second important factor. The directive on energy efficiency of the European Union (EU, 2012), for example, requires that member states enhance energy efficiency. German legislation obligates large companies to implement energy audits (section 2.3). The aims of this step are to observe and control energy consumption. The German Federal Emission Control Act (BImSchG, 2013) is another example and gives standards for the CO_2 emissions of steam boilers.

Sustainable energy supply for use in production is an upcoming objective. It includes innovative efficient technologies and low energy consumption with renewable energy technologies (e.g. solar-thermal systems). Because these technologies are often still of limited profitability (Hensler, 2009), their use is dependent on the corporate identity of a company, but also on its marketing strategy and customers.

1.3 Solar-thermal systems

Solar-thermal systems for residential applications are fully developed today and are widespread all over the world. About 350.1 million m^2 of glazed water collector area was in place in 2012. This is equivalent to thermal power capacity of 245 GW.

Figure 1.4 illustrates the distribution of installed collector area for several regions (BSW, 2012; IEA, 2014). Europe has its biggest markets in Germany and Turkey. These are far behind China, which is the most important region for the solar-thermal industry. In contrast to the rest of the world, where vacuum-tube collectors are dominant, the most common collector type in Germany is the flat-plate collector. There, 85% of all solar-thermal systems are based on this collector type. Small systems to prepare domestic hot water dominate the market there. Hence, the average collector area of a German solar-thermal system is about 9.3 m². However, larger systems with collector areas of 50 m² or more for residential applications are no longer exceptions.

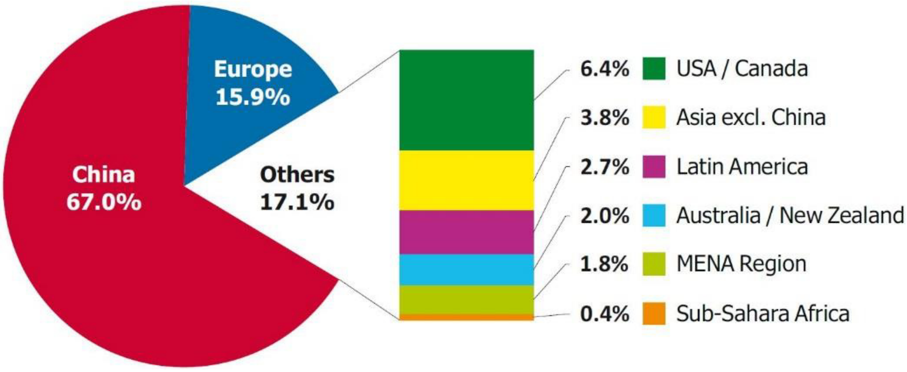

Figure 1.4: Regional Segmentation of Installed Collector Area (IEA, 2014)

More than one thousand systems are in operation today in Germany. Some of these systems reach collector areas of a few hundred square meters and a respectively high thermal capacity (BSW, 2012).

Despite these impressive facts concerning installed capacities of solar-thermal technology, it currently contributes only a very small portion of the final energy demand. Compared to the world primary energy use, this is just 0.001%. Even in Germany, continuously increasing solar-thermal capacities also contribute only a small part of the overall energy supply. As Figure 1.5 illustrates, all renewable energy sources supply 10.3% of the thermal energy needed in Germany. Solar-thermal technology, with all the 1.6 million systems installed in 2012, thereby supplies only a portion of 0.4% (BMU, 2012).

Both, technical equipment and performance of such systems are also adequate to supply process heat. However, it is much more difficult to integrate solar-thermal power into industrial processes than in residential buildings. As a consequence, solar process heat systems as in use today are not technically mature and, most important, not all standardised.

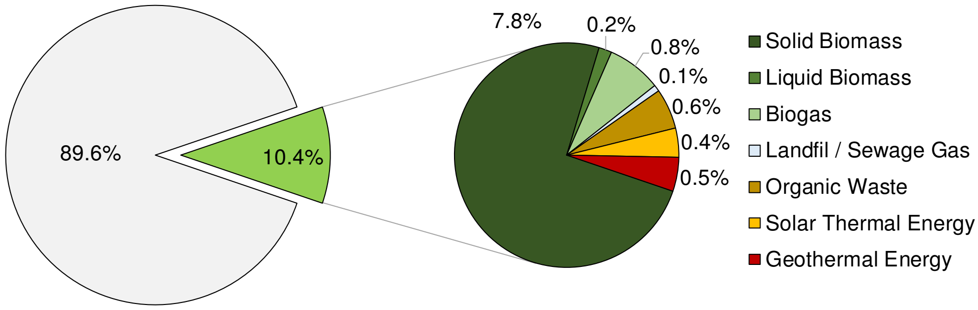

Figure 1.5: Contribution of Renewable Energies to German Thermal Energy Demand 2012 (cf. BMU, 2012)

Many of the solar process heat (SHP) systems work still as demonstration plants configured for specific applications. This means intensive planning and a very intensive monitoring of the starting phase, which is then required for every new system. A real standardisation for such cases has not yet taken place, which is preventing further spread of the technology.

Nevertheless, SPH-systems can support conventional process heat systems with low-grade heat of up to 100°C in a sufficient manner and, thereby, reduce fossil energy consumption.

1.4 Objectives of this research

The intention of this research was to enhance the use of SPH-systems to support or replace conventional process heat systems in the food industry. The initial objective was to provide a low-grade heat supply considering waste heat, with the final objective of a sustainable overall system. Such systems could not only contribute to significant reduction in CO_2 emissions but could also reduce energy costs over the long term. This will be made possible by applying an intelligent system configuration based on standard components, with simple integration into existing systems and processes.

There are just a small number of large SPH- systems in operation today, which are mainly demonstration plants with specific planning and application backgrounds. How to achieve a holistic system approach considering conventional-process heat systems, waste heat potential and supply processes, as the basis for a solar process heat system, is not clear in all cases.

Facing these deficiencies, the focus became the development of a methodology to assist not only energy engineers and decision-makers, but also planners. This methodology will be described in Chapter 3 and aims to configure the system design with specific consideration of the implementation of a SPH-system in a conventional-process heat system. Therefore, this methodology covers the following objectives:

- Analysis of energy consumption in order to develop energy balance.
- Analysis of energy supply and distribution networks to illustrate the energy flow.
- Analysis of production processes and energy consuming applications with respect to the recording of energy load profiles.
- Analysis of waste heat potentials and development of concepts for the integration of waste heat.
- Identification of suitable processes, applications and integration points for solar-process heat based on the previous analysis work.
- Development of methods for the analysis of energy flow based on the collected and analysed production processes.
- Development of concepts for solar-process heat supply.
- Modelling and simulation of concepts with relevant sensitivity analyses.
- Technical and economic system evaluation as well as optimisation of the developed systems, to define an optimum configuration for integration.
- Development of recommendations for planning and implementation of a SHP-system.

Comprehensive knowledge of the company energy supply is very important and requires documentation with energy balances, specific key figures or Sankey diagrams. Waste heat recovery is another significant aspect of heat supply and SPH-system integration. Detailed analysis is required to configure an energy efficient basis for solar-process heat and to consider the company requirements for economic efficiency and sustainability. These will be the main approaches for the development of the methodology (Chapter 3).

Thus, this research project was intended to develop and implement coherent system concepts with a more focused approach to their relevant application in the food industry. Hence, the results are not only a significant contribution to scientific knowledge; they also contribute to the benefit of the food industry and especially to the brewery and dairy branches.

The research is supported and enabled by analysis of real systems, specifically the companies of

- Dairy *Zott SE & Co. KG* (Mertingen, Germany)
- Brewery *Herrnbräu GmbH & Co. KG* (Ingolstadt, Germany).

2 Literature review

2.1 Industrial process heat demand and supply

As with primary energy consumption in other parts of the world (Section 1.1), the energy supply in Germany is also primarily based on fossil fuels. Coal, gas or oil provides nearly 80% of the total energy consumption – about 324,000 ktOE in 2012 (Figure 2.1). This causes CO_2 emissions of 768 Mto. The situation is similar in the EU28. In 2012, fossil fuels provided about 76% of the primary energy demand (about 1,780,605 ktOE), the combustion of which caused 4.558 Mto of CO_2-emissions. With its energy efficiency directive, the EU aims to reduce primary energy consumption to 368,000 ktOE by 2020 (EU, 2012). Renewable energies contribute just 11.2% in Germany and 10.3% in the EU28 to the energy supply (EUROSTAT, 2014; BMWi, 2014).

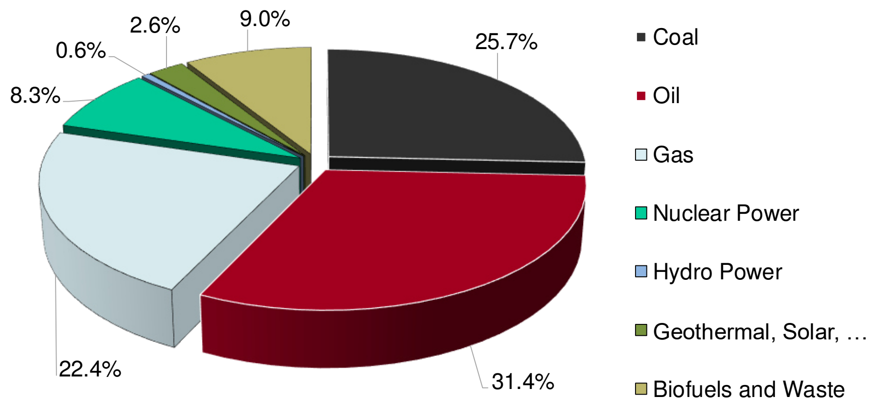

Figure 2.1: Primary Energy Sources in Germany 2012 (cf. IEA, 2015)

Not only for Germany but also for the EU28, the most important primary energy source is oil, followed by gas. The import quota of oil in Germany is near 100% and more than 85% for gas. EU28 nations produce only 15% of its oil and 30% of its gas consumption (EUROSTAT, 2014). Consequently, there is a major dependency on the oil and gas producing nations, which are mostly acting as monopolists, and of which a majority are based in political unstable regions. Therefore, it is an objective of the EU to reduce this dependency by increasing energy efficiency, and also by an expansion of renewable energies (EU, 2012).

Industries in Germany cover their energy demands in a comparable manner. Apart from negative effects of using huge amounts of fossil fuels (Section 1.1), energy costs are of growing interest today. Although the proportion of gross production value in 2012 was only 2.0% (BMWi, 2014) for the industrial sector, energy has become a much more important production factor, and has risen by 30% since 2000. As Figure 2.2 shows, the industry´s expenditures for fuel oil and gas have grown continuously for more than ten years, only interrupted for a short period by the economic crisis in 2008. Against the background of continuously increasing costs, efforts to increase energy efficiency and reduce energy demand have risen as well. With this continuing tendency, the application of technologies not previously economical is becoming possible.

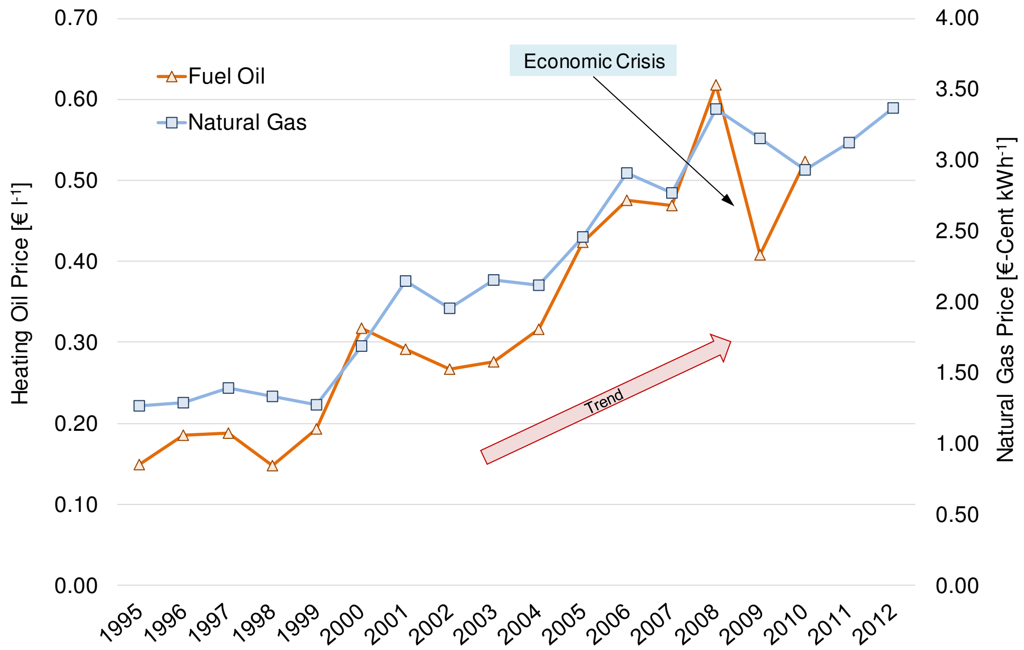

Figure 2.2: Energy Prices for the German Industry (cf. BMWi, 2014)

The public discussion today deals usually with the supply and distribution of electricity. Thermal energy is often neglected in these discussions in Germany and in most other European countries. However, a major part of the final energy needed is thermal energy. Figure 2.3 describes that the industry sector consumes nearly three quarters of its energy demand as thermal energy process heat, space heating or hot water supply.

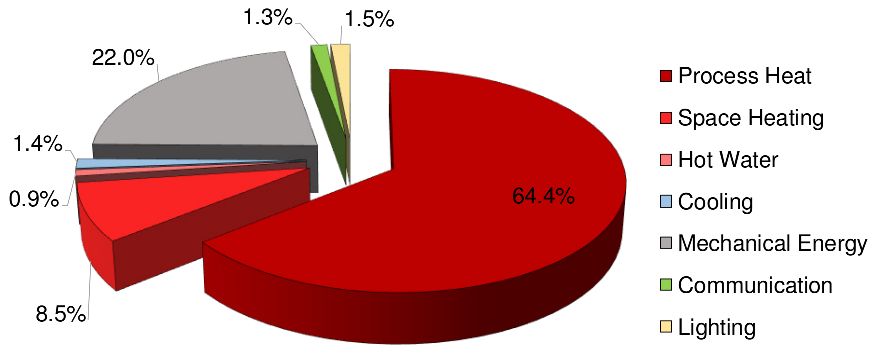

Figure 2.3: Industrial Energy Demand in Germany 2012 (cf. BMWi, 2014)

This thermal energy is needed for all industrial processes and other industrial applications. Figure 2.4 gives an overview of applications in different industrial sectors. There are many applications at high temperatures, such as glass and ceramic manufacturing, or processing of iron and steel. These temperature levels require conventional energy sources. However, there are also many processes and applications that occur at < 200°C. Chemical products, the paper manufacturing industry, and especially the food processing industry, produce in part, or even completely, within this temperature range.

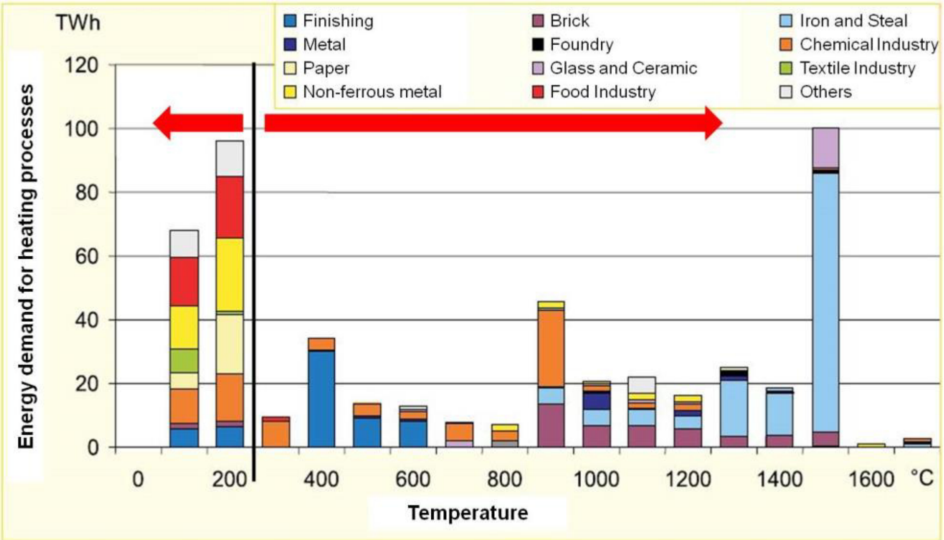

Figure 2.4: Process Energy Demand and Related Temperature Levels (Aidonis, 2005)

In Germany, the industrial sector consumed 718.6 TWh in 2012, which is about 22.2% of that used by the EU28 industrial sector. As mentioned before, nearly 75% or 530 TWh is used as thermal energy. Considering the total thermal energy use by industry, the absolute potential for solar-process heat can be defined. The thermal energy demand, and hence the potential for solar-thermal applications at < 200°C, is about 180 TWh, with 72 TWh at < 100°C (EUROSTAT, 2014; BMWi, 2014).

In addition to the temperature levels, Figure 2.4 presents several branches within the industry sector where most of the processes and applications are within a temperature range up to 200°C and significant parts in a range of up to 100°C. Branches with exceptionally favourable conditions are the chemical industry, the paper industry and the food industry. To emphasise the suitability of some of these industries concerning solar-process heat supply, a more detailed view on the temperature levels and specific energy demands is necessary. Therefore, the thermal energy needs will be distinguished into different temperature ranges: < 100, 100 – 500, and > 500°C (Aidonis, 2005; Lauterbach, 2011).

Table 2.1 lists the results of this analysis for different industries. The food industry uses, besides the paper and chemical industry, most of its thermal energy at temperatures < 100°C. One third of processes within the paper industry and more than 40% within the food industry also fall within this range. In contrast to that, the glass and ceramic industry demands only 5% of its thermal energy at temperatures < 100°C (Aidonis, 2005; Lauterbach, 2011).

Table 2.1: Thermal Energy Demand in Industrial Sectors*

Industrial Sectors	Thermal Energy Demand Proportion		
	<100°C	100–500°C	>500°C
Food Industry	43%	57%	0%
Paper Industry	34%	66%	0%
Chemical Industry	21%	22%	57%
Glass and Ceramics	5%	2%	93%

*without SH and DHW (cf. Lauterbach, 2011)

With regard to solar-thermal technology, temperatures a bit higher than 100°C can also be interesting. Therefore, the range of 100 – 500°C shown in Table 2.1 has to be divided into more steps and analysed in more detail. With 43% of thermal energy consumption demand below 100°C, as illustrated in Table 2.1, the food industry already provides advantageous conditions for solar thermal.

The detailed analysis shows that nearly 85% of thermal energy used in the food industries is below 150°C and only 16.4% is above. In contrast to the total industry sector described in Table 2.1, these all occur under advantageous conditions. Of the entire industrial thermal energy demand, 24% is for temperatures < 150°C.

Table 2.2: Thermal Energy Demand below 250 °C *

	Thermal Energy Demand Proportion			
	<100°C	100–150°C	150–200°C	200–250°C
Food Industry	42.9%	40.7%	16.4%	0%
Industry Sector	12.7%	11.3%	4.1%	1.2%

*without SH and DHW (cf. Lauterbach, 2011)

In addition to the process heat demand illustrated in Table 2.1 and Table 2.2, the energy needs for space heating and service hot water have to be considered. For the food industry, this is about three quarters of the process heat demand in the temperature range up to 100°C.

2.2 The food industry

The food industry is one of the most important industrial sectors in the EU28. About 4.2 million people work in 286,000 companies and generate a total manufacturing turnover of more than EUR 1,048 billion. SMEs dominate the sector and generate, with nearly 65% of all employees, more than 50% of that turnover. There has also been continuous growth of 1.8% for the last ten years. Dairies and the beverage industry (including breweries) are important subsectors within the food industry in Europe and are responsible for one third of the economic power within this sector (EC, 2009; FD, 2015).

This situation is comparable in UK and Germany. Behind automotive and mechanical engineering, the German food industry, with 5,900 companies, 560,000 employees and a turnover of EUR 172 billion, is the third largest industrial sector. The growth of this sector is a consequence of increasing exports (Destatis, 2014; BVE, 2014). The UK food manufacturing industry is the fourth biggest industry sector there with 6,000 businesses 400,000–500,000 employees (Hall, 2011).

2.2.1 Process heat in the food industry

The significance of the European food industry is not only an economic one. It is responsible for 5.3% of the world's industrial energy consumption. This is 29 billion tOE or 10% of the European industrial energy consumption (Eurostat, 2014). In Germany, the food industry consumes 8.1% of the industrial final energy demand. This was about 58.5 TWh of electricity and thermal energy in 2012 (Destatis, 2014). The UK food industry is responsible for 11.5% of the industrial final energy consumption. This was 36.8 TWh of electricity and thermal energy in 2010 (Hall, 2012)

On average, the proportion of thermal energy in the food industry is more than three quarters and dominates the total energy use. However, depending on specific aspects, there are also some subsectors with a high electricity demand. A large proportion of dairy energy, for example, is represented by cooling of quickly perishable raw materials and finished products. This leads to disproportionally high electricity use for chillers. An interesting fact is that renewable energy is not yet of importance in this subsector, as Figure 2.5 illustrates. Renewable energies currently contribute only 1.3%, and therefore represent a potential opportunity that is under-exploited in the food industry.

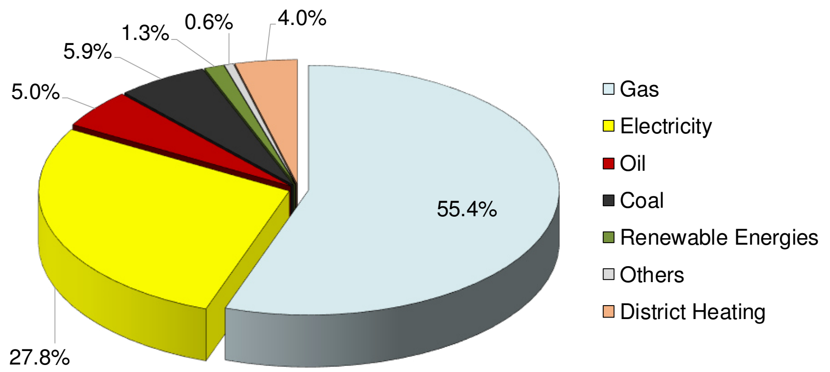

Figure 2.5: Energy Sources in the German Food Industry (cf. Destatis, 2015)

Concerning a renewable energy supply and especially solar-process heat, relevant branches have to be highlighted. The total energy consumption, and even more importantly, the temperature levels, are the criteria. Figure 2.6 shows the most important industrial subsectors in the food industry, which are responsible for more than 90% of the energy consumption in this sector. With an energy use of 8.8 TWh a^{-1}, sugar processing is the largest energy consuming subsector, followed by dairies and meat processing. Breweries use, together with the non-alcoholic beverage producers, nearly 5.5 TWh a^{-1} (Destatis, 2015; EnergieAgentur.NRW, 2012).

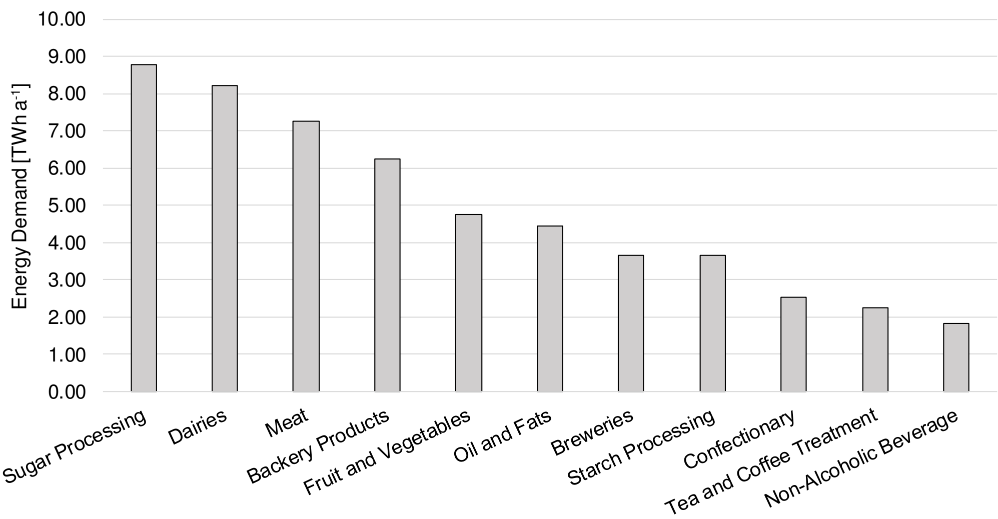

Figure 2.6: Final Energy Demand of the German Food Industry (cf. Destatis, 2015)

The food industry consumes 83.6% of its thermal energy at temperatures below 150°C (Table 2.2). However, there are also industrial sectors where temperature levels for processes and other applications are even lower. The meat processing or confectionary demand, for example, requires heat at temperatures < 100 °C. With a few exceptions, most steps of milk processing do not require temperatures of more than 140 °C. This is quite similar to breweries, where the highest temperature levels are necessary for the boiling processes in the brew house and limited to about 100 °C. Many breweries also produce non-alcoholic beverages. Hence, this subsector is also analysed in Figure 2.7. Process temperatures here are limited to 80 °C.

The analysis of the food industry shows promising conditions in several industrial sectors concerning renewable, and particularly solar-process, heat supply. Thermal energy consumption combined with temperature levels point at dairies and breweries connected with non-alcoholic beverage production as particularly interesting for solar applications.

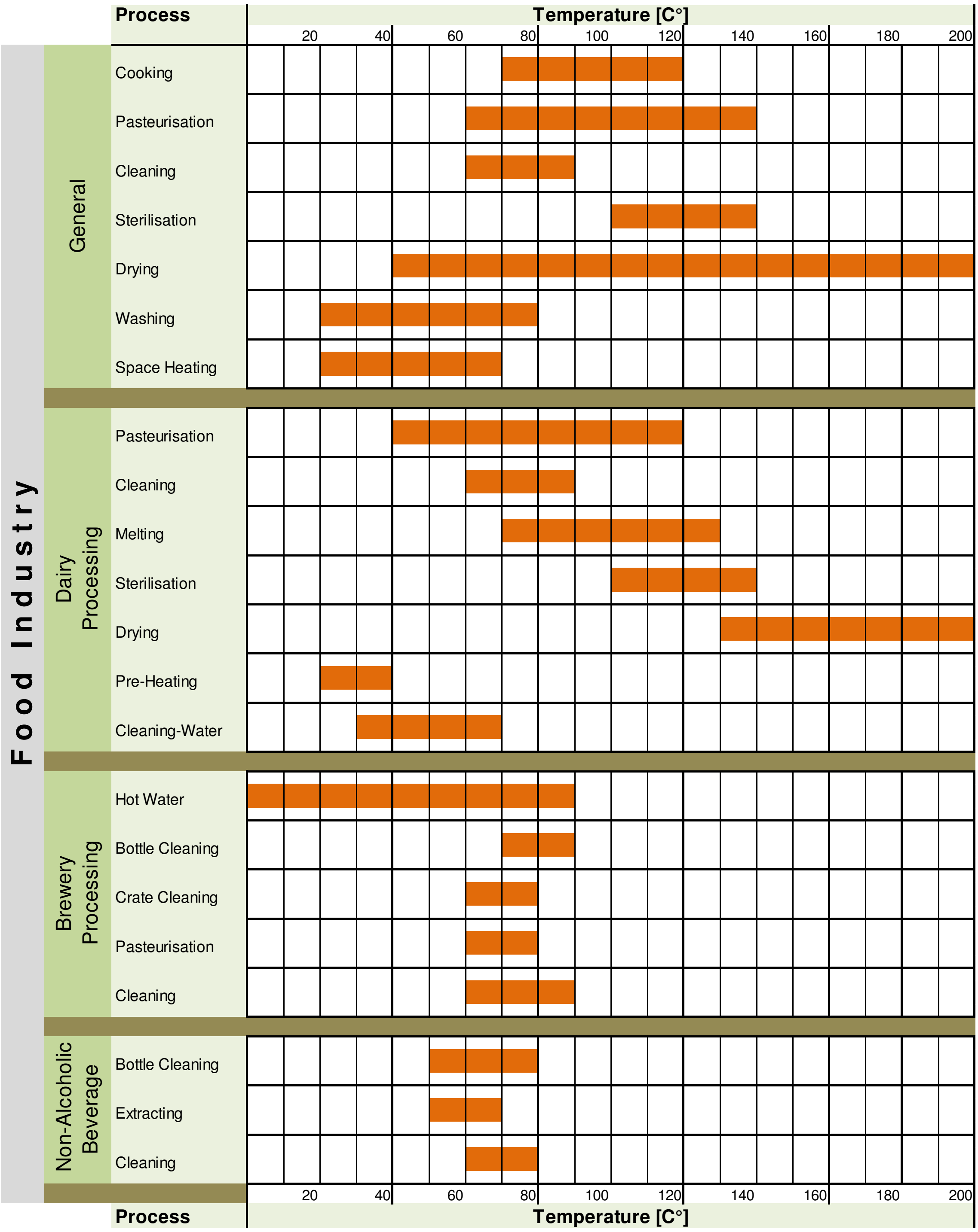

Figure 2.7: Selected Process Temperatures in the Food Industry
(cf. Vannoni, 2008; cf. Schweiger, 2001)

Besides energetic aspects, breweries and dairies are growing industries with relevant branches all over the world. Beer production has grown by 2.5% and milk production by 2.2%, each year since 2000 (Statista, 2015; Barth Haas Group, 2014).

2.2.2 Dairies

There was a substantial consolidation of the German dairies over the last few decades. While in 1950 more than 3,400 dairies were in operation, today less than 170 companies with an average staff of about 175 employees share the market. These figures reflect the trend from small dairies spread all over Germany with local milk production and processing, to only a relatively few large companies handling industrial milk processing and the addition of a few milk processing specialists with specific products. The very large number of dairies after the Second World War was founded on very restricted cooling possibilities, and the resulting necessity of processing the milk near its origin. With the development of various, more effective cooling devises, even mobile ones based on tanker trucks, it was more and more possible to carry the milk over long distances from the fastest growing dairies, leading at the end to the described progress. The total raw milk production in 2012 was 29.8 million tonnes. The largest product group is consumer milk followed by yogurts and various yogurt products. German dairies generated a turnover of more than EUR 22.9 billion in 2012, with a share of more than 75% of the home market. Furthermore, a small number of dairies in Germany dominate the market. Ten big dairies process more than half of the available raw milk and about two thirds of the annual turnover (Milchverband e. V., 2014).

A similar consolidation took place in France, UK and Netherlands (Ramirez, 2004). The number of dairies in UK for example decreases from 336 in 1985 to 102 in 2000. In contrast the average milk input per dairy growths from 45,400 to 105,000 tonnes per year. The production trends for different dairy products for German, France, UK and Netherlands are also similar. This demonstrates the comparability of the dairy industry.

With regard to the energy used in the German dairy branch, the consolidation means also, the concentration of huge energy demands in a few companies. Based on total demand, an average dairy uses about 42.3 GWh of electricity and thermal energy each year. However, there are also big differences between the dairies with regard to their product portfolio. Specifically cheese dairies, followed by consumer milk producing companies, need less energy for each litre of processed milk than do the yogurt and dessert producing dairies. Moreover, differences between the proportions used of electricity and thermal energy exist. While cheese dairies need hardly any electricity because of very low cooling requirements of the finished products, the yogurt and dessert dairies consume a disproportionally large amount of their electric energy for refrigerated storage.

The average energy cost factor of the dairy industry is at 1.5% with regard to gross production value. This is less than the energy cost factor of the German industrial sector (Section 2.1). At dairies, it depends on the product portfolio and can reach nearly 15%. Hence, the benefits from investments in energy saving technologies depend strongly on the company-specific energy cost factor. (EnergieAgentur.NRW, 2012)

Today, thermal energy is realised with steam boilers and sometimes supported with CHP-Units for low-temperature heat, and fossil energy sources dominate thermal energy supply. As illustrated in Figure 2.8, about 90% is based on gas or oil. Heat distribution networks work with steam or hot water as heat transfer media.

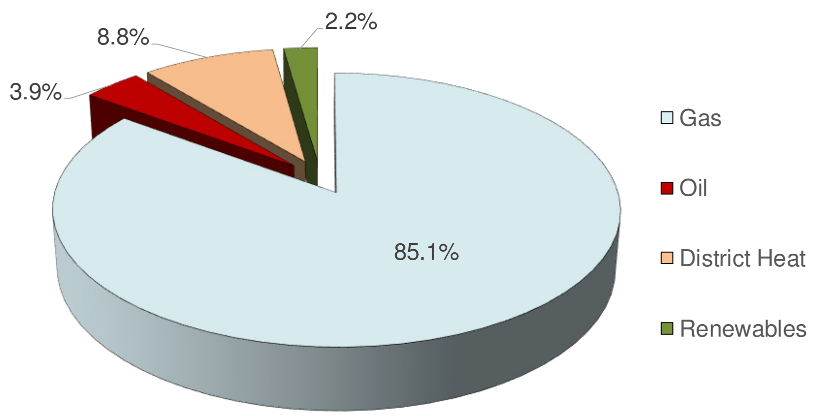

Figure 2.8: Energy Sources for Process Heat in Dairies (cf. Destatis, 2015)

Besides the oil and gas needed for the operation of steam boilers and CHP-Units, electric energy is required for chillers, air-compressors and production facilities. Depending on the product portfolio, the demand for electricity can reach a proportion of about 40%. Specific energy demands refer to processed raw milk and are at 0.02 – 0.18 $kWh_{th}\ l_{Milk}^{-1}$ for thermal energy consumption, and up to 0.13 $kWh_{el}\ l_{Milk}^{-1}$ for electricity consumption (EnergieAgentur.NRW, 2012).

Milk is a very sensitive product and perishes quickly. Therefore, clean processing is an important factor for the dairy industry. Within the manufacturing processes from raw milk to the finished product, various steps are necessary. Figure 2.9 illustrates the basic processing of milk from the delivery of raw milk to the finished products, on basis of the main production steps and the demand for cooling and process heat. The products are highly diverse and can be distinguished not only by the production process required, but also by the energy needs for its manufacturing. Most dairies in Germany are specialists making a product or product group. Hence, the specific energy demands, as mentioned above, of both thermal energy and electricity can vary considerably.

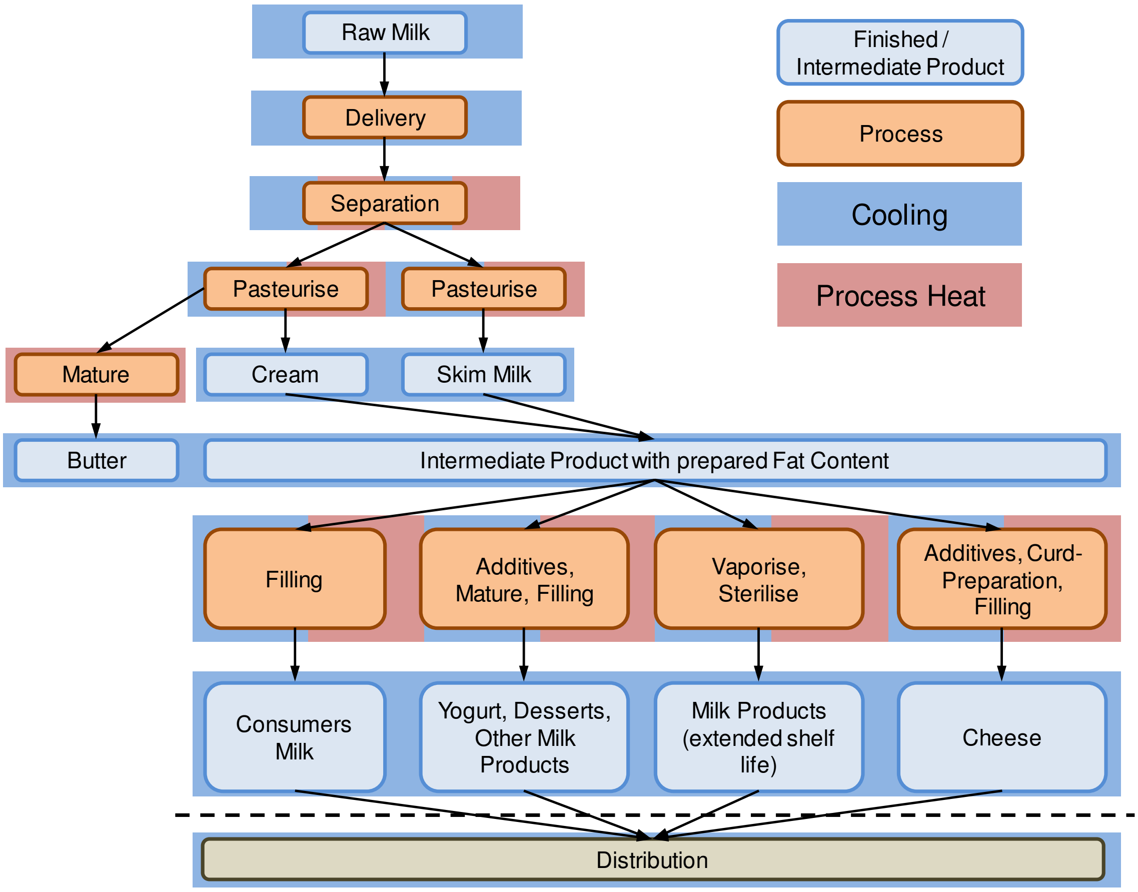

Figure 2.9: Basic Scheme of Milk Processing

2.2.3 Breweries

The beer market is global and today is dominated by only a few large brewery groups, each with many brands in several locations. The five biggest of them produce nearly half of the world´s beer consumption whereas number one, AB InBev (Belgium), is responsible for 18%, with an annual output of 353 million hl (2012). This group distributes about 200 brands at 140 locations. Besides the global players, there are also explicit regional markets with many small and very small breweries with annual production capacities of a few thousand hectolitres. With an output of 545.2 million hl in 2012, the European market contributes 28% to the world's beer production. Germany (94.6 million hl) ranges behind Russia (97.4 million hl) as the second largest beer-producing nation in Europe, but is small compared to the world's largest brewery group. The beer production in the UK is about 45.2 million hl and third largest in Europe (Barth Haas Group, 2014).

Following a period of growth after 1950, German beer production reached a maximum in 1992 of 120 million hl and has continuously decreased since then. As illustrated in Figure 2.10, the annual production fell to a value of 95 million hl.

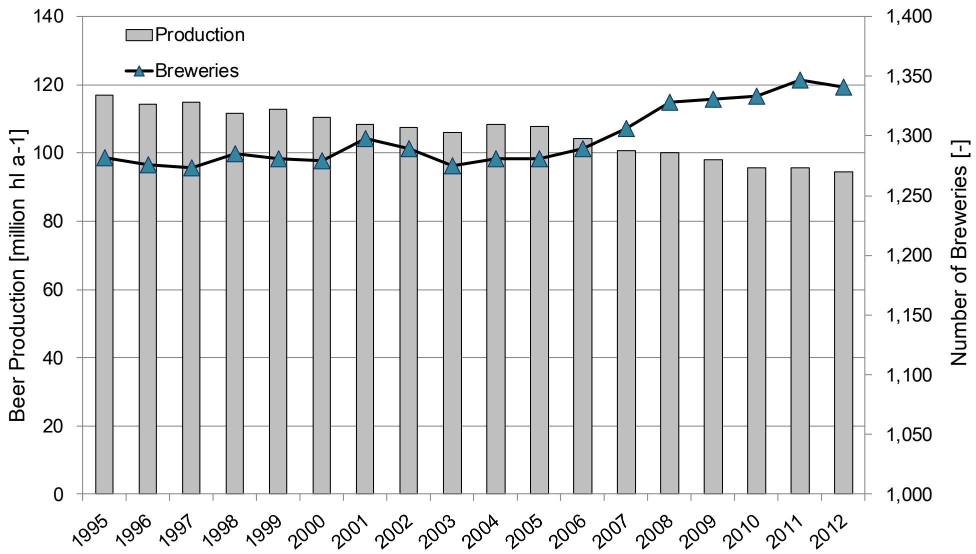

Figure 2.10: Annual Beer Production and Number of Breweries in Germany
(cf. BRAUER BUND, 2014)

In contrast to decreasing beer consumption, the number of breweries has stabilised at a relatively constant level. In 2012, 1,341 breweries with about 27,000 employees were in operation. The turnover of the brewing sector was at EUR 8 billion in this year. Contrary to the dairies described in Section 2.2.2, most of the breweries are small companies with an annual production of less than 5,000 hl (Table 2.3). About 920 breweries belong to this category. There is furthermore, a trend towards a growing number of breweries in this group. First in Bavaria, so called “pub breweries” led this development. Medium-sized breweries are responsible for about 30% of the production. Only 42 large breweries with an annual output of 500,000 hl or more are in operation. However, this group produces nearly three quarters of the German beer (BRAUER BUND, 2012). A similar trend of declining beer consumption can also be observed for the UK. The number of breweries decreases from 140 in 1976 to 52 in 2006 (BBPA, 2010). This reflects a trend towards large breweries which dominate the market.

Table 2.3: Classification of German Breweries*

	Classification of Brewery Size		
	Small-Sized	Medium-Sized	Large-Sized
	< 5,000 hl	5,000–500,000 hl	> 500,000 hl
Breweries	68.5%	28.4%	3.1%
Production	0.9%	25.2%	73.9%

*(cf. BRAUER BUND, 2015)

With a final energy demand of 3.7 TWh in 2012, the breweries belong to an important subsector within the food industry. Almost three quarters of the energy demand in an average brewery is needed as thermal energy. As Figure 2.11 shows, fossil fuels (gas followed by oil and coal) dominate the supply of thermal energy. Renewable energies are not significant yet and contribute only 2.4%. Of the final energy, 28.7% is used as electricity.

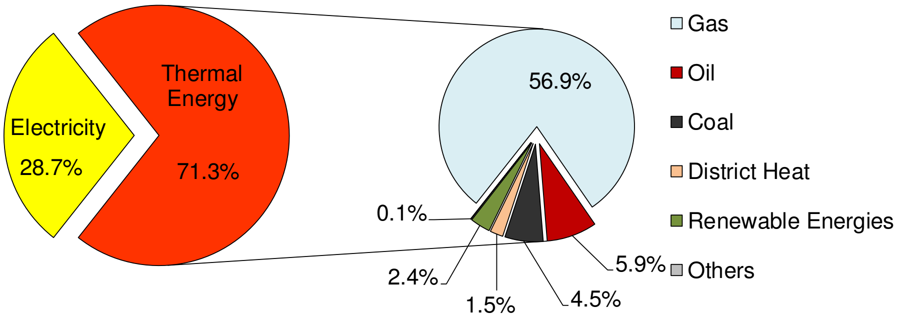

Figure 2.11: Proportion of Energy Sources in German Breweries (cf. Destatis, 2015)

To assign the energy demands in a brewery to the different users and production sections, a more detailed knowledge of the products and their processing is necessary. Products of breweries are not as manifold as dairy products, regarding the general manufacturing methods, and are thus much more comparable. The two product groups are bottom-fermented beer and top-fermented beer. A distinction between them is the kind of maturation used in the fermenting cellars. Therefore, Figure 2.12 illustrates the basic production scheme of a brewery. There are five sections in a modern standard brewery:

- *Brew house*
  Section for manufacturing of wort (bottom- and top-fermented kinds of beer)
- *Fermenting Cellar*
  One for top-fermented and one for bottom-fermented beer
- *Storage Cellar* or *Ageing Chambers*
  The storage cellar for the secondary fermentation of bottom-fermented and the ageing chambers for the top-fermented beer
- *Filtration*
  For the filtration of bottom-fermented kinds of beer
- *Filling*
  Filling section with bottle and barrel cleaning

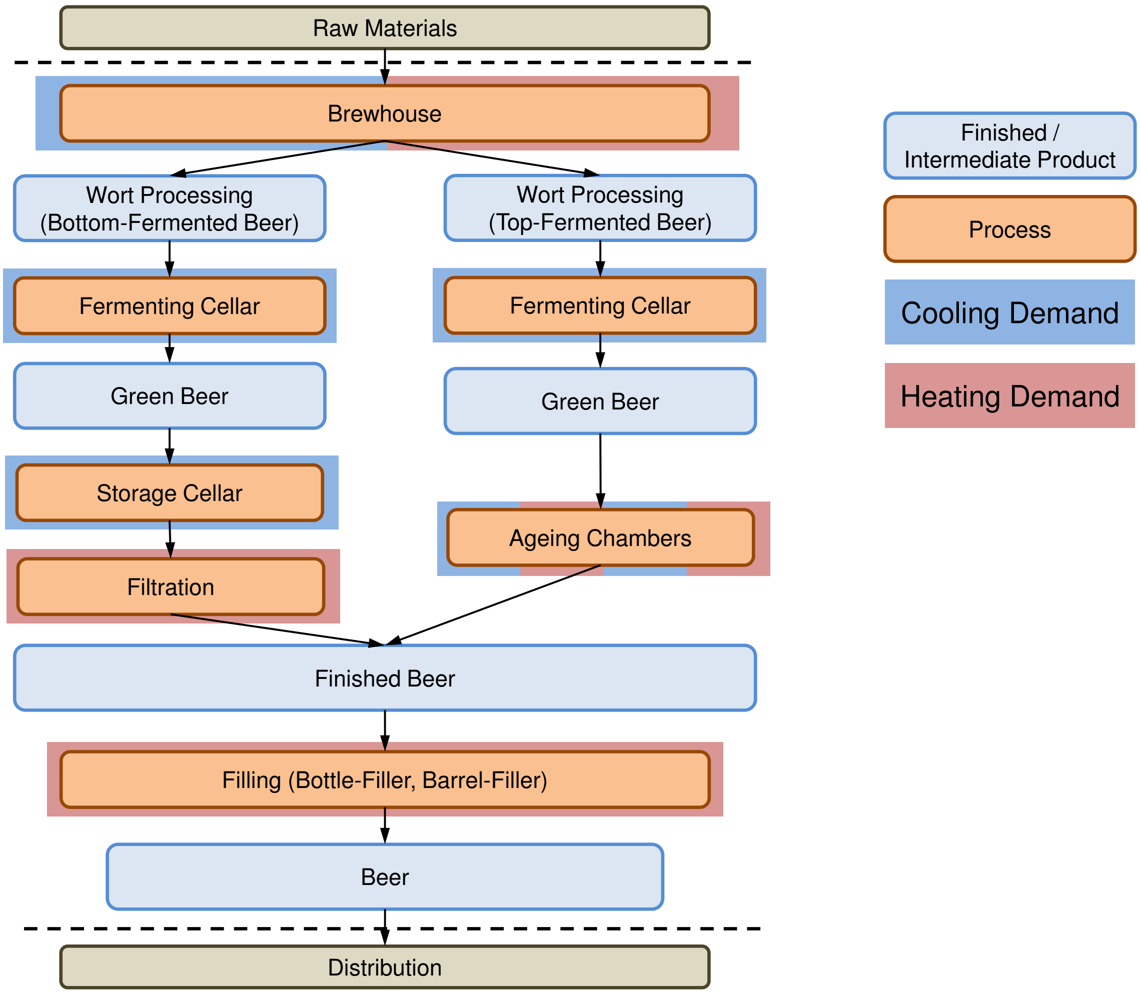

Figure 2.12: Basic Production Scheme of a Brewery

Thermal energy in a brewery is mainly used in the brewhouse (43%) and the filling section (40%). The remaining energy consumption is found in various cleaning applications, filtration, service hot water or space heating. The largest consumers of electricity are the chillers. Cooling energy is necessary in several production sections. These are, most importantly, the fermenting cellars as well as the brewhouse, but also the storage cellar (EnergieAgentur.NRW, 2012).

The definition of specific energy consumption at breweries is based upon the unit of production, which is a hectolitre of beer (hl_{beer} = 0.1 m^3). German breweries consume 18 – 75 kWh_{th} hl_{beer}^{-1} and 7 – 39 kWh_{el} hl_{beer}^{-1} (Energieagentur.NRW, 2012). Kunze (2011) defined optima for different brewery categories (Table 2.4) and distinguishes the production of beer and non-alcoholic beverages. A brewery with an output of 250,000 hl a^{-1} requires therefore 31.4 kWh_{th} hl_{beer}^{-1} of thermal energy and 8.3 kWh_{el} hl_{beer}^{-1} of electricity demand for beer production.

Table 2.4: Optimum Energy Demand of Production of Beer and Non-Alcoholic Drinks*

	Thermal Energy Demand [kWh_{th} hl^{-1}]		Electricity Demand [kWh_{th} hl^{-1}]	
Size of Production	20,000 hl a^{-1}	250,000 hl a^{-1}	20,000 hl a^{-1}	250,000 hl a^{-1}
Beer	36.1	31.4	9.9	8.3
Non-Alcoholic Beverages	9.4	8.0	2.1	1.7

*(cf. Kunze, 2011)

Besides production and energy converting technology, the demand for both thermal energy and electricity, also depends on other facts:

- *Production capacity,*
- *Workload,*
  Strongly depends on the production capacity and additionally on the total annual production,
- *Number of employees.*

As a result, the higher the workload the less the specific energy demand; however, there are of course also more energy efficient breweries and less energy efficient breweries. This is comparable to the dairy branch.

Large but also small and medium-sized breweries have large potentials to reduce water and energy demand. Sturm (2012) analysed the UK breweries in this area and did a case study with a medium-sized brewery. She found, that energy efficiency investments are often restrained as this is not core business of the brewing companies. Breweries argue with the quality of their product that can be affected by new technologies. Additionally, small and medium-sized breweries must not compete with large breweries on the mass market and can achieve higher prices for the products on niche market. Hence, the reduction of production cost is not top priority of the brewery. However, raising fuel prices and requirements of the national legislation will increase pressure on the small and medium-sized breweries. For Sturm (2012) this must be supported by strategies that convince the companies from the implementation of new and existing technologies.

2.3 Sustainability in the food industry

Sustainability is nothing new for the manufacturing of goods. Hans-Carl von Carlowitz defined sustainability first for the forest industry in 1713 (Hauff, 2014). The sustainability definition includes therefore the stability and the capability of regeneration within a system. With today's depletion of energy resources, environmental pollution and global warming, the negative effects of conventional industrial production have come into focus. Many people hold this aspect of production responsible for these problems and demand change. A way towards sustainable production shall be the solution.

Hauff (2014) describes a model with three pillars of sustainability, along with their dimensions. Figure 2.13 illustrates these dimensions social, environmental and economic. None of the dimensions can be considered independent, as a consequence of manifold interconnections. This is very important as each dimension affects the others.

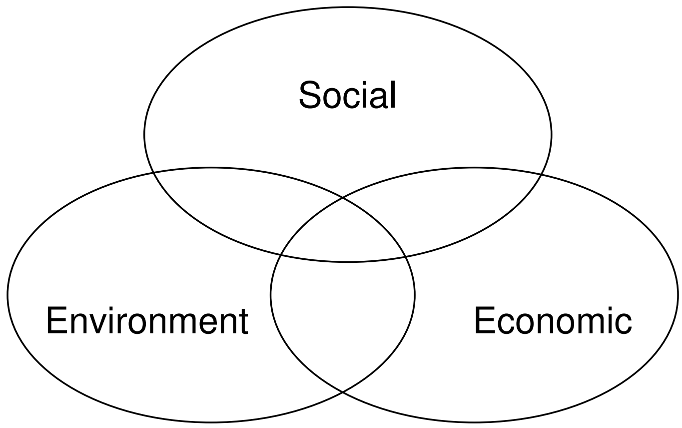

Figure 2.13: Three pillars of sustainability (cf. Hauff, 2014)

The environmental dimension includes, for example, land use, water use or atmospheric emissions, but also energy consumption. The food processing industry has a large influence on this dimension (Baldwin, 2009), all along the value chain. This means, of course, that aspects like land or water use for food processing is mainly based on agriculture. However, the food processing industry is also a large consumer of energy (Section 2.2) with many possibilities for improving the situation. LEE (2011) analysed the possibilities of the US food industry, and exemplary for the dairy industry, regarding water consumption, waste from the companies and energy efficiency. Simulations studies show, that investments in energy saving technology can reduce the fossil fuel consumption by 50% but also save 2.7% of costs. Energy efficiency and renewable energy systems are good approaches to contribute to more sustainability, but it is also important not to neglect the economic dimension.

The following review of the literature illustrates approaches for sustainability on the energy part of the environmental dimension.

2.4 Energy auditing

Energy auditing becomes an important aspect of the reduction of industrial energy consumption, and also for energy efficiency. Such an audit shall ensure the existence of a data background and help the companies to understand their individual energy consumption. Standards (Section 2.4.1) guide and commit the industry to energy audits. However, there are also challenges with completion of energy audits (Section 2.4.2).

2.4.1 Standards for energy auditing and energy management

The reduction of primary energy demand by increasing energy efficiency 20% is the main objective of the Energy Efficiency Directive of the European Union (EU, 2012). All member states are obligated to transfer the directive into country specific legislation. Standards developed for industry shall contribute to the energy efficiency objectives.

Consequently, the German legislation requires from all companies not defined as SMEs, an energy audit every four years with the DIN EN 16247-1 (2012). This standard provides a framework for the audit process. It is necessarily very general to be applicable for all industrial sectors and for each kind of company. Its main objective is the documentation of energy consumption for different areas (processes, buildings and transport) and demands that companies manage their energy behaviour. Important aspects are the acquisition and analysis of energy data to derive objectives for energy efficiency. The evaluation of energy efficiency measures (EEM) shall motivate the companies to implement them. However, there is no obligation. Independent specialists carry out that audit. The long period between audits is a disadvantage. The risk is that companies might focus their activities just on the energy audit and neglect, for example, continuous control of their energy data. Another deficiency is that the standard does not affect SMEs. The legislation just recommends an energy audit in these cases.

Other member countries of the EU have already committed to, or have prepared current legislation with similar standards (Eurochambres, 2015) comparable to the German DIN EN 16247-1:

- The Environment Agency of the UK, for example, requires from companies not defined as SMEs, to do an 'Energy Savings Opportunity Scheme' in 2014 (Environment Agency, 2015).
- Austria for example committed companies not defined as SMEs, to do an energy audit based on the EN 16247-1.

More comprehensive than the DIN EN 16247-1 is the DIN EN ISO 50001 (2011). While the DIN EN 16247-1 is focused on the documentation of energy consumption of relevant areas and EEM, the DIN EN ISO 50001 is a complete energy management system. It covers all areas of a company and is ready for integration into an enterprise management system. This standard is intended to enable more efficient use of available energy and reduction of CO_2-emissions. Finally, it should help companies to become more competitive. The company management, therefore, defines clear objectives for energy consumption as a long-term strategy. The approach is intended to involve continuous control and improvement of energy use. Monitoring, key figures and benchmarks are tools to enhance the awareness of energy use. The DIN EN ISO 50001 involves continuous improvement and could be used by companies to improve their public image. However, mainly large companies work with this standard because it requires the implementation of organisational structures and use of staff working exclusively on energy topics.

The Associations of German Engineers publishes alternative standards to the DIN. The VDI 3922 (2012) is comparable to a manual and gives a structure for energy consulting. It is generally applicable to industry or other businesses, but less for a company’s own activities, than for energy consultants.

The VDI 4602 (2007) gives essential information to companies about how to implement and use energy management. In contrast to the DIN EN ISO 50001, it is not for certification but for self-management of energy activities and for motivation. It is first a very comprehensive guide and involves all areas of a company. Many aspects however, are similar to the DIN EN ISO 50001. This means, for example, there should be long-term strategies by top management and implementation of a continuous process of improvement (Figure 2.14).

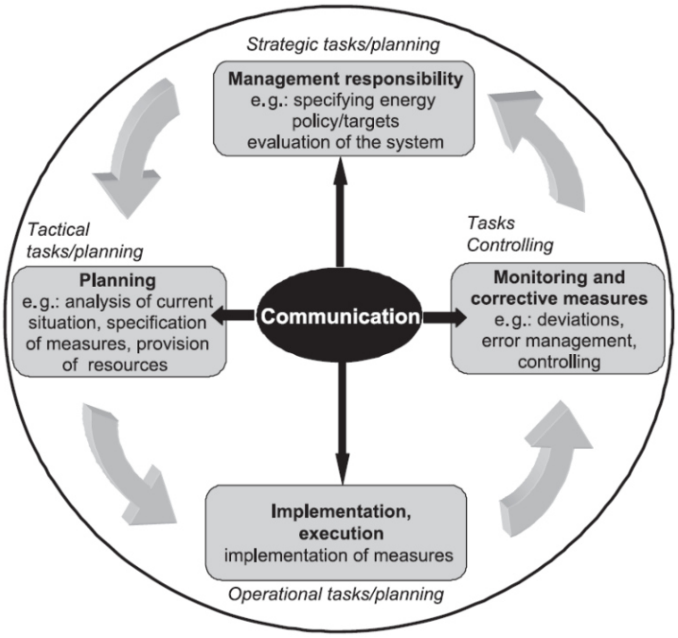

Figure 2.14: Circle of action of an energy management system (VDI, 2007)

Energy audit and energy management in general, mean the implementation of a deliberate use of energy in industry. The standards of DIN, VDI or ESOS shall therefore support the companies to comply with the requirements of the legislation for energy efficiency. However, this could be just a minimum standard that recommends to companies what knowledge is necessary to improve energy efficiency and reduce energy consumption. They do not provide a guide for creating energy efficiency measures. When procedures are rough and too general, the result will be differences in handling and varying results (Section 2.4.2). More specific energy efficiency guidelines could focus on individual industrial sectors and, most importantly, on all the technologies related to energy efficiency (Section 2.5).

2.4.2 Energy auditing in practice – results and challenges

The transformation of the Energy Efficiency Directive (EU, 2012) into country legislation is a significant step with regard to energy efficiency in the industrial sector. It requires for the first time by law (except by SMEs), documentation of energy consumption for relevant areas, and finally, to develop and evaluate EEMs. The same is recommended for SMEs. Energy auditing is nothing new. Standards and guides for energy auditing have been available for several years and are used by many companies.

Doing an energy audit, however, does not constitute in any way, actual energy efficiency for a company. Trianni and Cagno (2011) found several barriers that prevent the implementation of EEMs. Lack of capital, lack of time, other priorities and too little background information on energy efficiency for decision making are the most frequent barriers mentioned by SMEs in a survey. Consequently, energy efficiency depends on various facts and requires more attention to the backgrounds of the energy engineers. Fleiter et al. (2012) confirmed those barriers and focused further on the specific characteristics that distinguish EEMs and demonstrate their inhomogeneity. The consequence is an inadequate understanding of EEMs, which is another thing that prevents their implementation (Fleiter et al., 2012). The approach to a solution involves a classification scheme with twelve characteristics (e.g. payback period or knowledge for planning and implementation). Each of these characteristics is evaluated with several attributes to help define the diversity of EEMs. Finally, using the scheme, EEMs are classified from ‘low adoption rate’ to ‘high adoption rate’ and shall provide a better understanding for decision makers in industry. The result is also helpful for guiding energy efficiency policies to support the most promising options for energy efficiency. However, the scheme was developed without the feedback of energy engineers as user.

The implementation of EEMs requires, on one hand, knowledge about efficiency technology. On the other hand, it requires detailed information on company energy data to define exact efficiency potential. Therefore, the data must be available at a process level to understand all the interconnections between individual energy consumers (Thollander et al., 2014). In contrast to total energy data of a company, this is mainly not the case. This lack of detailed process energy data prevents the implementation of EEMs by companies because they do not know their efficiency potential. It also prevents a focused energy policy. Thollander et al. (2014) also uncovered errors in the available energy data from energy audits and additional differences between the data from several countries. Thollander et al. (2014) analysed the results from application of energy audit information.

The application of the energy management standard shows also deficiencies in practice. Dörr (2013) analysed the ISO 50001 regarding energy efficiency on a process level for the European industry. He came to the conclusion, that the standard gives just very general requirements. Low manpower but also missing expertise impedes a detailed analysis of the energy supply systems at companies. However, Dörr (2013) identifies technical knowledge on energy efficiency as as essential for the improvement of energy efficiency. He recommends therefore general checklists for the decision makers. Ates (2012) analysis the application of the ISO 50001 for the energy intensive industry in Turkey. He found on basis of a study that just 22% of the Turkish industry uses the energy management standard. This prevents a continuous improvement of energy efficiency but also the improvement of the competitiveness of the industry. Solutions to change this situations are for example promotion of energy efficiency but also education and training of the responsible staff. Dörr (2013) and Ates (2012) identified for the systematic improvement of energy efficiency with the ISO

50001 and recommend to increase the knowledge of the responsible company staff. However, both do not provide explicit methodologies.

2.5 Guides for energy efficiency

The motivating factors for energy efficiency in the industry are not only the legislation, economic aspects (costs of energy) and the development of efficient technologies; but also social trends like the awareness and desire of consumers for sustainability (DENEFF, 2015). The general significance of energy efficiency is increasing (Destatis, 2015) but is also dependent on the company size. Figure 2.15 shows the main differences regarding energy efficiency, between large companies and SMEs.

Energy Efficiency	Large Companies	SMEs
Importance	high	medium / low
Expertise	high	limited
Qualified Staff	specific for energy matters	limited available additional task of other staff
Financial Strength	high financial flexibility	limited financial flexibility

Figure 2.15: Energy efficiency in large companies and SMEs (cf. EEP, 2015)

The evaluation of energy efficiency is general and provides a measure of energy consumption compared to production volume (Eq. 2.1) (cf. Thiede, 2012).

$$Energyefficiency_{general} = \frac{outputof\ goods}{inputof\ energy} \qquad \text{(Eq. 2.1)}$$

Companies use this term as the basis for evaluation of their individual energy efficiency. Various studies – available from different authors – shall support the industry with increasing energy efficiency. These studies range from pure descriptions of energy saving potential, to ‘energy efficiency guides’ developed for specific industrial sectors, forms of energy or energy supply technologies.

2.5.1 Energy saving potentials

VBW (2012) and EEP (2013) distinguish energy saving potentials for industrial sectors and for different energy consumers (e.g. process heat, space heating or electricity for cooling). It is estimated that the food industry is able to reduce its electricity consumption by 3.3% and its fuel consumption by 9.7% (EEP, 2013). Process heat (52 PJ) and space heating (32 PJ) are the applications with the largest absolute potential for energy savings in the entire German industry (VBW, 2012). BMWi (2007) defines for the industry additional potential energy savings based on technical and economic background. These results include, for example, technical potential energy savings for electro motors of 55 PJ (24%) and economic potential energy savings of 22 PJ (9%). This demonstrates the potential of distinguishing energy efficiency focused on technology from energy efficiency focused on economics. Studies for energy saving potential give the industry and industrial sectors first indications. However, these are just rough calculations. Furthermore, application to a specific company is limited, because the figures from the studies do not distinguish company size or product portfolio. The classification of a specific company requires detailed knowledge on its energy consumption.

2.5.2 Energy efficiency measures

Guidelines for energy efficiency measures focus on energy supply and energy consumers in industry. The initial emphasis is on widespread technologies that are of great importance in multiple industrial sectors. The main objective of the guides is the illustration of possibilities to achieve defined energy saving potentials (BMWi, 2010; Hessen, 2009; LfU, 2009). The guides follow a similar structure and

- describe energy supply and consumption technology,
- define potential energy savings,
- illustrate possibilities to achieve energy saving,
- evaluate energy saving measures.

Many of the measures are discussed in a similar way in all the guidelines (Figure 2.16). This points out the importance of crosscutting technologies (e.g. cooling systems or electric motors), applied in most industry sectors.

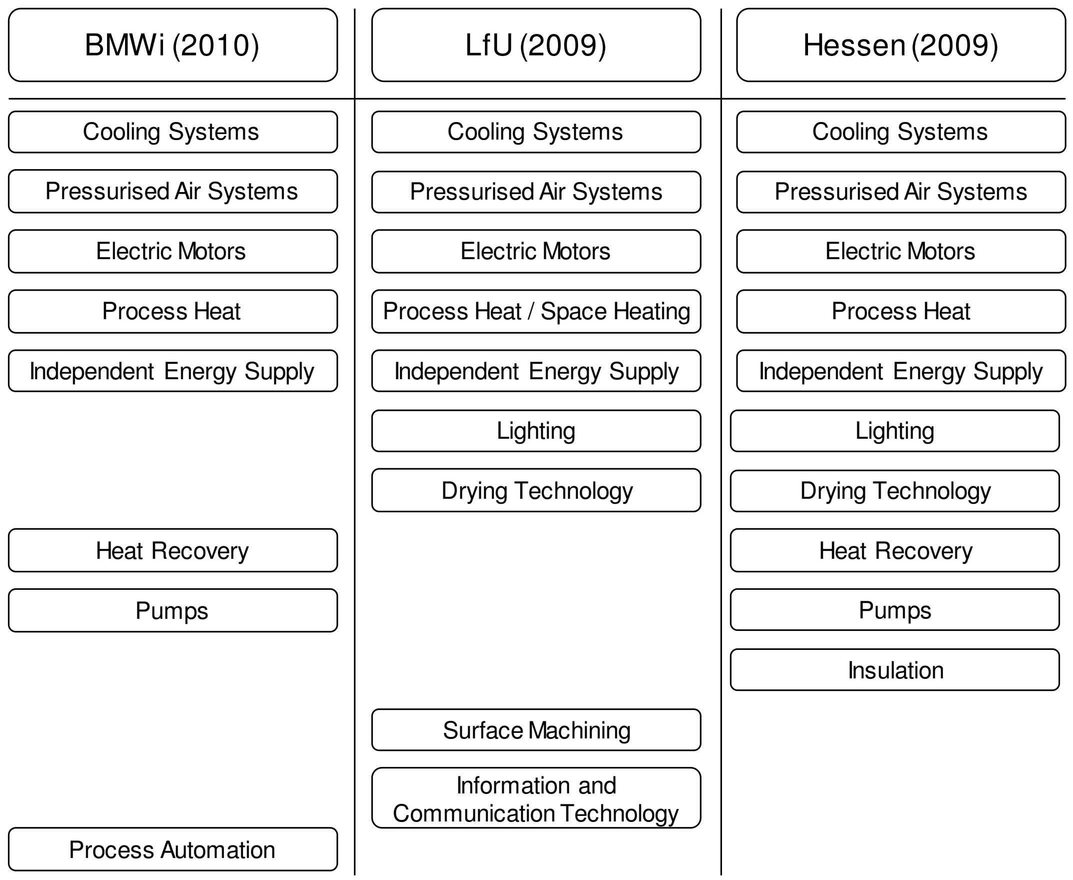

Figure 2.16: Topics discussed in the guidelines (cf. BMWi, 2020; LfU, 2009; Hessen, 2009)

LfU (2009) and Hessen (2009) start the guidelines with a general introduction of energy efficiency and emphasise the necessity of detailed knowledge on energy consumption and specific key figures for the evaluation of energy efficiency. Hessen (2009) introduces additional tools for the definition of energy saving potential like pinch analysis or the potential for application of simulation.

The following measures selected from the guidelines describe some exemplary results. BMWi (2010) describes cooling systems as technology for cooling processes and space cooling at various industries. Despite their widespread use, their energy efficiency is a limited topic. Table 2.5 categorises the potential energy savings of cooling systems regarding system components, operation conditions and cooling demand.

Table 2.5: Energy saving potentials of cooling systems*

Components	Operation conditions	Cooling Demand
Highly efficient motor	Cleaning of heat exchanger	System optimisation
up to 5%	up to 3%	up to 10%
Highly efficient compressor		Insulation
up to 5%		up to 10%

*(cf. BMWi, 2010)

LfU (2009) determined that electric motors for driving pumps, compressors or conveyer systems were primary consumers of electrical energy. About 70% of the electricity consumption in the German industry is used in this way. The potential increase in efficiency is between 2% and 10%. The life cycle costs of an electric motor are dominated (90%) by energy costs. Hence, the amortisation period for investments in highly efficient motors is 1 – 3 years.

Hessen (2009) describes pressurised air as an inefficient working fluid. Only 4-7% of the system energy consumption is available as propulsion energy. Hence, it is necessary to design and maintain pressurised air systems carefully. The compressors should be located near the consumer and designed with a pressurised air rate at the optimum compressor working condition. Short piping with optimal pipe diameter limits pressurised air losses. Continuous maintenance is necessary to detect leakage from pipes and to keep the air pressure as low as possible.

Summarising, the guidelines very general. They give just a rough estimation of energy efficiency and some approaches for the utilisation of potential energy savings. Economic evaluations are available for only a few measures. The guidelines do not provide a procedure for design or implementation of the measures to be taken. The information collected and analysed can be seen as background for different audiences, from company staff to design engineers.

2.5.3 Energy efficiency for industrial sectors

Comparable to the guidelines described in Section 2.5.2, there are also guidelines available for industrial sectors. These consider the characteristics of a specific sector and focus on restricted regions (e.g. Canada or the UK). This enables energy efficiency tailored to the intended industry sector and therefore, makes the guidelines more significant.

These guidelines pursue a variety of objectives. As Figure 2.17 illustrates, these objectives range from illustration of measures to improve just energy efficiency, or reduction of carbon emissions, to measures for saving energy for cost reduction. It is not clear in any case, for what group of users the guidelines are defined. Only the guidelines of Brush et al. (2011) and Galitsky et al. (2003) intend to support energy and plant managers. However, the plant manager is not defined and the energy manager is described as staff with a wide range of responsibilities (from 10% to 100% energy tasks). Only these two guides both address EM specifically, and aim to support it with decision making.

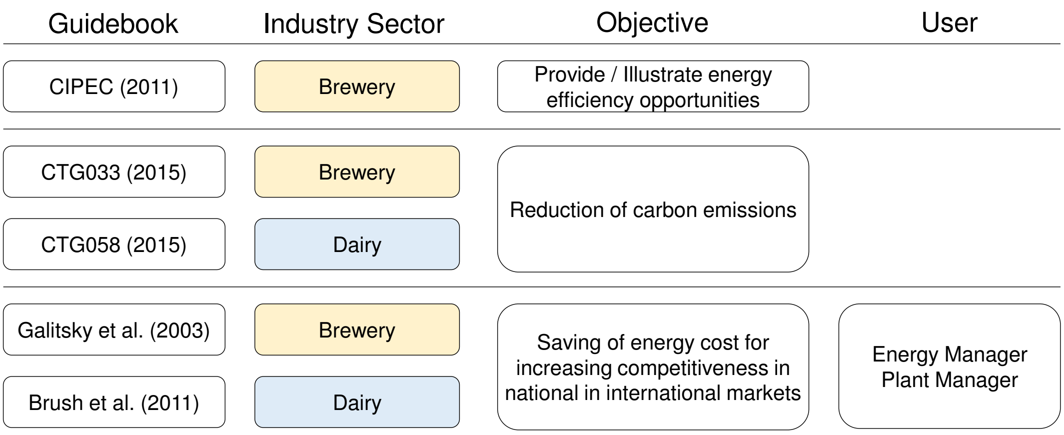

Figure 2.17: Exemplary guidelines for energy efficiency

All guidelines start with a similar analysis of the intended industrial sector considering energy demands and some facts about the producing companies. CIPEC (2011) for example describes the energy demand and production output of the Canadian brewery industry. It also defines categories of brewery size and gives an overview of the number of breweries as well as the industrial sector leader. CTG058 (2015) complements economic facts with the history of development of the analysed dairy industry subsector over one decade.

The second part of the guidelines is description of the products and illustration of production. On one hand, Galitsky et al. (2003) analysed the manufacturing of beer, giving the production sections of a brewery and the main processes. On the other hand, CIPEC (2011) gives just a rough description of some aspects of beer production. Brush et al. (2015) combines analysis of production and processes of several dairy products with an energetic analysis, with results being key figures for specific products. This part gives an impression of the differences between the brewery and dairy subsectors. Breweries produce various kinds of beer, but all with a very similar production flow and similar energy demands. Dairies produce various kinds of milk products, but with various production flows and different energy demands.

CTG033 (2015) and CTG058 (2015) go on with methods of data acquisition and definition of important metering points of production equipment and energy supply. CIPEC (2011) recommends in a comprehensive manner the performance of energy audits or even the implementation of energy management systems. The guidelines also emphasise the strategic level of energy management and energy efficiency in this connection. This requires first, definition of the economic or technical framework conditions for efficiency measures.

The third part, available in all guidelines, is about real measures to achieve energy efficiency. Galitsky et al. (2003) and Brush et al. (2015) distinguish processes as well as cross cutting technologies and utilities. Therefore, the guidelines recommend various energy efficiency measures. This procedure is similar with the guidelines of CTG033 (2015) and CTG058 (2015). Generally, the efficiency measures include energy supply, maintenance, system control and system monitoring, process operation or the implementation of new technologies. The following examples illustrate some measures described in the guidelines.

- CIPEC (2011) starts with the analysis of the electricity load profile and focuses on load peaks of overall production. It recommends shifting the loads to decrease peak power demand. This measure is characterised as exclusively economic, because it does not save energy, but reduces costs for capacity-based rates.

- Galitsky et al. (2003) recommends implementation of vapour condensers into the wort boiling process for heat recovery, and estimates potential energy savings of up to 60%.
- CTG033 (2015) recommends reducing the number of CIP units with an intelligent CIP schedule, and increased load of the remaining CIP. The potential energy savings, are not specified.
- CTG058 (2015) compares the technologies of flash and tunnel pasteurisation for beer production. It gives several optimisation opportunities such as improvement of insulation or maintenance of pumps. It also describes alternative pasteurisation technologies.

The last part is a brief summary. Galitsky et al. (2003) provides an additional overview of the discussed measures with payback periods and primary energy savings. This is similar to CTG058 (2015) but complements it with the emission saving potential. In its summary, CIPEC (2011) illustrates the influence of the Canadian brewery industry on the greenhouse effect, and explains the calculation of a carbon footprint.

The guidelines remain essentially a compilation of measures. An action plan for creating a consistent methodology is not identifiable. Instead, the guidelines introduce and recommend various measures without a holistic approach to energy efficiency. Only Brush et al. (2011) and Galitsky et al. (2003) consider company energy managers in their guides, but even they do not use feedback from such managers.

2.5.4 Methods for energy efficiency

Independent from those guidelines, Seai (2013) aims to provide project management tools for the implementation of energy efficiency measures. This is called ‘Energy Efficient Design (EED) methodology’ and is not specialised for specific industry branches or efficiency technologies. The EED methodology consists of three phases: facility energy balance, analysis and challenge, and implementation. Specific with this methodology, is that it combines design and implementation with energy management activities. The application methodology is for energy professionals (called EED experts) that have the required expertise in energy efficiency. These are commissioned by company members (called EED owners) who define the frame work for energy efficiency and decide about implementation. Finally, this methodology has a very rough structure and within the first two phases, is just comparable to an energy audit. It provides analysis of basic energetic behaviour and defines energy efficiency measures. In contrast to an energy audit, the EED approach is focused on implementation of energy efficiency measures and integrates additional energy management issues. Energy engineers from companies are not considered for development of this methodology.

Low-grade heat systems have an important role for achieving energy efficiency. Depending on the configuration, such systems can be used for the implementation of waste heat recovery. Some studies have proposed procedures to adapt low-grade heat systems for heat recovery. Semkov (2014), for example, analysed the heat supply for sliced, cooked meat production and defined a procedure for it. His approach included an internal heat exchange within a closed system using the pinch method. The aim was to reduce fossil fuel supply based on analysis and optimisation – with the integration of new technology – of an existing system with the integration of a redesigned heat exchanger network. The work of Semkov (2014) is about the use of specific tools at a scientific level, but not for energy engineers.

Walmsley et al. (2014) goes one step further and defines low-grade heat systems as heat recovery loops (HRL). The main objective is a system configuration for indirect use of waste heat, because this is necessary for industries with batch or semi-continuous processes. The case study was a dairy with independent plants and Walmsley et al. (2014) intended to connect these using HRLs. After definition of hot and cold temperatures, all the available sources and all the suitable sinks are connected to the HRL. An adapted pinch method is used for the definition of the temperatures and the heat capacities of the sources and sinks. The resulting configuration parameters are not only background for waste heat recovery but also enable the integration of solar process heat. Walmsley et al. (2014) recognises that the high investment costs for the necessary infrastructure is one major barrier to the addition of solar process heat. His approach to solve this challenge was common use of the HRL infrastructure (e.g. piping and storage) for the processes of both waste heat and solar heat. An important part of this is heat storage. Walmsley et al. (2014) compares HRL with constant and with variable storage temperatures. They aim to investigate the potential savings from integration of solar process heat with existing storage, and the advantage of variable storage temperature. A specific solar heat storage structure is therefore no longer necessary. Walmsley et al. (2014) demonstrated promising integration options for solar process heat as an additional heat source – which means heat recovery first – in a heat recovery loop with slightly better results for variable storage temperatures.

Walmsley et al. (2015) investigated further the technical solution of solar process heat integration with a heat recovery loop with variable temperature storage. It is again here, the objective to lower SPH-system costs by sharing existing low-grade heat supply equipment. The focus is on variations for integration of the solar process heat. Walmsley et al. (2015) compared serial and parallel (relative to other heat sources) integration of solar process heat, with a heat recovery loop without solar process heat. The most promising option is serial integration. This theoretical work of Walmsley et al. (2015) is also on a scientific level. Application by energy engineers is not possible at this stage. An application by energy engineers in the real world would require comprehensive work to translate the findings into guidelines.

Law (2012) analysed waste heat potentials of the UK food industry and investigated several technologies for the recovery of low-grade waste heat. 27% of the final energy use of the UK food industry are wasted each year. Most economical is a direct reuse of this waste heat for other processes at the same plant (Law, 2012). Depending on waste heat quality (temperature, capacity), there are various additional options. Law (2012) analysed for example heat pumps for an upgrade of the waste heat but also the possibility of Rankine or Kalina cycle to use the waste heat for power generation. He concluded that waste heat recovery is essential for the efficiency of the company. Investments in energy efficiency measures could increase in fact of raising energy costs but also legislation. However, Law (2012) does not present a methodology that supports energy engineers at companies.

2.6 Solar process heat

Renewable energy sources in general, and more particularly SPH-systems, today contribute very little to the energy supply of industry. Vannoni (2008) found that in 2006, all over the world, only about 90 SPH-systems with a combined thermal power of 25 MW and a total collector area of 35,000 m² were in operation. By 2013, this capacity had grown to 57.6 MW of thermal power and a collector area of 82,400 m² (Brunner, 2013). More than 40% of today's SPH-systems supply energy for the food and beverage industry, but this is still only a small number of systems. Table 2.6 gives an overview of the installed systems and illustrates the collector area as well as the resulting thermal power. This emphasises the favourable conditions for energy savings in the food industry. However, the fraction of current savings of the total energy demand of the food and beverage industry is negligible, and below 0.1%.

Table 2.6: SPH-systems in the food and beverage industry

	Collector Area [m²]	Thermal Power [MW_{th}]	Fraction of total Energy Demand [%]
2006 (Vannoni, 2007)	4,800	3.4	0.021
2012 (Brunner, 2013)	35,000	24.5	0.028

The European solar-thermal market is dominated by small systems for domestic applications (DHW and SH). In 2012, about 40.5 million m² of collector area, with a thermal power of 28.3 GW, was installed in Europe. Germany, with 16 million m² collector area and 11.2 GW of thermal capacity, is the biggest market there (ESTIF, 2013) followed by the Turkey and Austria. United Kingdom is the twelfth larges market with a proportion of 1.2% of the European collector area. The installed collector area of 0.71 million m² and 0.5 GW of thermal capacity. Figure 2.18 illustrates the development of the UK market. The annual installed capacity in Europe has a peak in 2008 and decreases since then (IEA, 2014). This peak occurred for the UK market in 2010 (Figure 2.18).

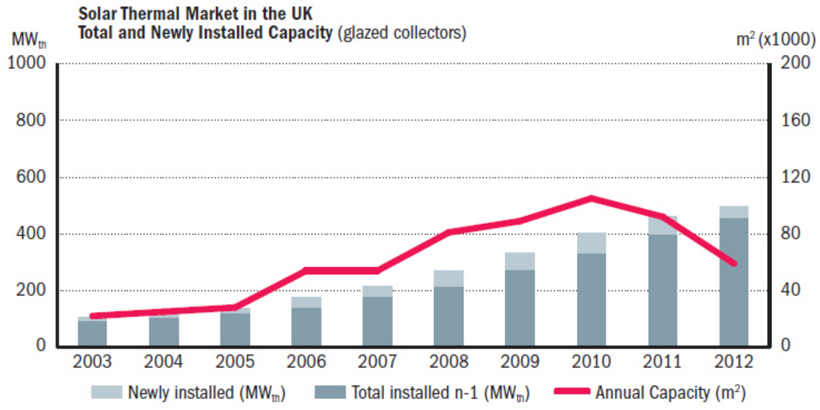

Figure 2.18: Solar thermal market in the UK (Estif, 2013)

Small systems for domestic applications are fully developed and available to the market as standard solutions (Meyer, 2012). For large systems, however, the availability of standard solutions is limited. The components (e.g. collector, storage) are mainly the same as in small systems, but the system hydraulics and related control strategies become more complex. This is not least, a result of a multivalent process heat supply and increasing system complexity. With regard to the spread of large solar-thermal systems, this is a major challenge, and is even much more important for SPH-systems, where new energy consumers differ from case to case.

However, the idea of a solar process heat supply is not a new idea. Already at the Paris Exposition in 1878, a system with a parabolic collector was presented which powered a printing press. In the early 1900s, a few SPH-systems were used to drive irrigation pumps. One system of this period is shown in Figure 2.19. During its operation time of only two years, this system powered an irrigation pump with a capacity of 23,000 L min^{-1} in Egypt. Motivation and interest behind these systems was at that time not very different from today:

- a lack of adequate alternative propulsion technologies existed,
- no other energy sources were available,
- alternative energy and / or alternative technologies were too expensive.

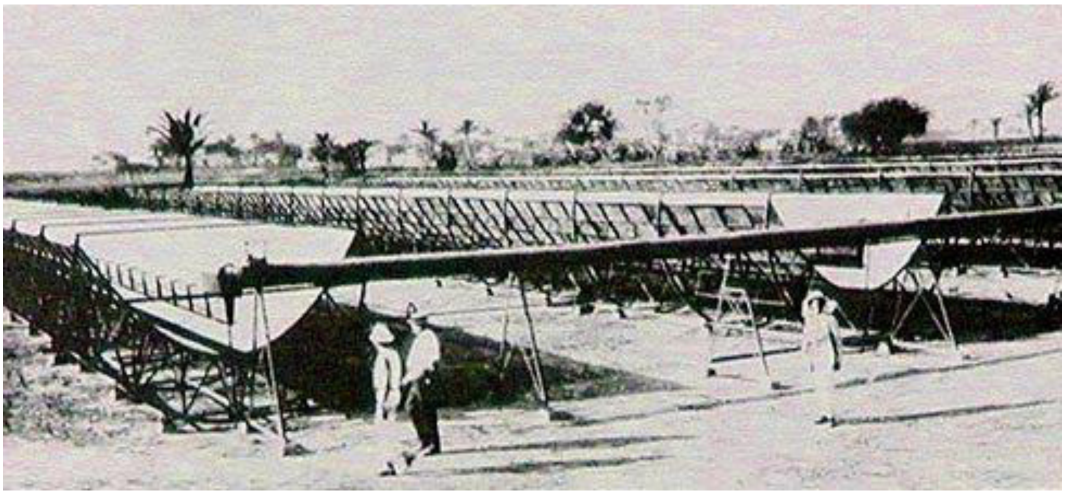

Figure 2.19: Solar parabolic system for driving an irrigation pump in Egypt in 1900 (Goswami, 2000)

Energy providing systems and technologies are no longer a problem today. In the 20th century, technologies for almost every application were developed. The electrification of the world as well as the use of oil and gas as energy sources led to a nearly unlimited availability of energy in some parts of the world. However, the energy needs of the rest of the world are now maturing, resulting in rapid and continuous growth in demand. The consequence is the increasing depletion of primary energy sources in the past decades connected to an unfavourable development of energy costs: rising costs over the long term, severe fluctuations and unsteadiness. Together with the negative effect of burning fossil fuels on global climate, these are motivations for a growing interest in SPH-systems.

With regard to their production costs and a growing awareness of a sustainable energy supply, many companies look for alternatives to conventional process heat systems. Not only industrial branches with huge energy demands continuously improve their internal energy supply and distribution. Besides the reduction of energy consumption with new production and energy conversion technologies, there is a focus on energy efficiency. Reducing energy demand is of course the first option open to every company. The second step is to become independent of fossil fuels.

2.6.1 Solar process heat systems in operation

SPH-systems provide the option of almost fuel free operation. Apart from the electricity for pumps and control devices, no other external energy input is necessary. Some exemplary SPH-systems will show the potential of the technology.

Washing containers in Spain

Since 2005, the Spanish company *CONTANK, S. A.* (Barcelona) has run an SPH-system to support the conventional energy supply used for their washing processes. The company specialises in the transport of chemicals. The transport containers have to be cleaned with hot water after every use. CONTANK decided to use solar process heat for pre-heating the washing water. A collector area of 510 m² (Figure 2.20) and a heat capacity of 357 kW_{th} provides the energy. A heat exchanger separates the collector and the storage circuits. The buffer storage (40,000 L) is connected to the cold water supply and provides its energy to the auxiliary storage (Figure 2.21). Here, the necessary temperature level of 70 – 80°C for the process is realised using a conventional steam boiler. The SPH-system contributes 490 MWh_{th} a^{-1} to the total energy demand of about 1,900 MWh_{th} a^{-1}, which is a solar fraction of more than 20%.

Figure 2.20: Building with flat-plate-collector array at CONTANK, S. A. (Meyer, 2007)

Based on an investment of EUR 262,500 and several funding measures, the net energy costs are 2.5 €-Cent kWh_{th}^{-1} and pay-back will be reached in about 12 years. Positive arguments for this system are

- favourable location with an annual irradiation of > 1,600 kWh m^{-2} a^{-1},
- high specific collector earnings of about 840 kWh_{th} m^{-2} a^{-1},
- low-temperature requirement of the supported process,
- continuous energy demand of the company throughout the year.

All these aspects lead to a positive overall result of this system (SHC, 2012).

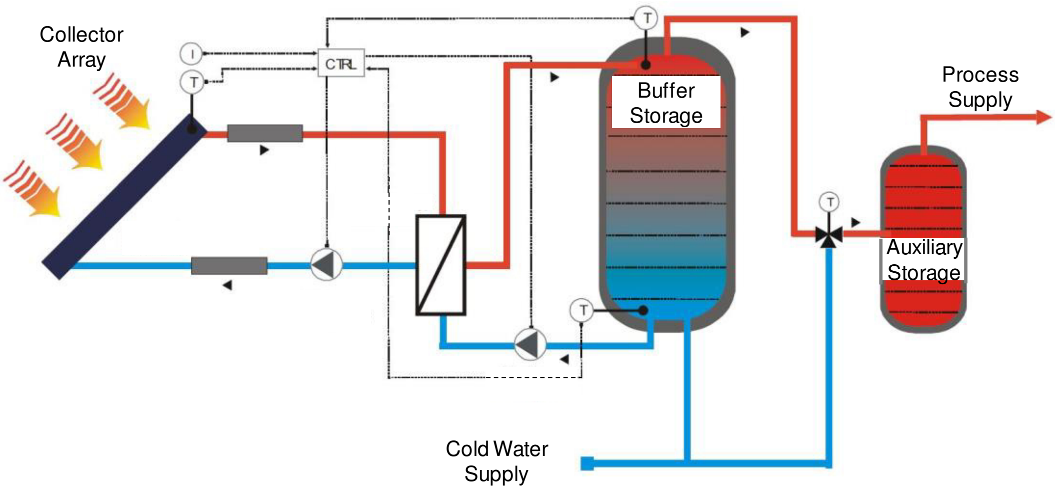

Figure 2.21: Schematic of the SPH-System at CONTANK (cf. SHC, 2012)

Heat supply for milk processing in a dairy

Another example for solar process heat supply is the system at Tyras S. A. Dairy in Trikala (Greece). It provides energy to the hot water network and supports conventional heat generation by a steam boiler (LPG). Since 2001, two collector arrays with combined area of 1,002.4 m² (Figure 2.22) and thermal power of 730 kW, supply energy to a buffer storage tank (50,000 L). The system was designed for optimally economic operation, not to reach a maximum solar fraction. Focus is on maximum specific collector earnings (kWh_{th} m^{-2} a^{-1}). Therefore, the system aims to cover 80% of the maximum load in summer in order to avoid stagnation and reduced earning. This configuration produces an average of 700 MWh_{th}

annually. Hence, the contribution of the solar process heat is just 7% of the total energy demand. With an investment of EUR 172,000 in combination with public funding, a ROI of three years was reached, based on the fossil fuel costs in 2001.

Figure 2.22: Collector array of the SPH-system at Tyras Dairy (Mayer, 2007)

Lauterbach (2011) analysed the potential of SPH-technology. As shown in Table 2.7, he identified 15.6 TWh of thermal energy savings related to solar-thermal applications in German industry. This energy demand could be covered with a collector area of about 35 million m² with a thermal power of 25 GW. This would mean about two and a half times the collector area now installed in Germany. Meeting the EU25 potential would require more than four times the collector area installed in 2010 (Estif, 2012).

Table 2.7: Potential of solar process heat for industrial applications*

	Solar process heat potential [TWh]	Solar process heat potential [GW]	Solar process heat potential [m²]
Germany	15.6	25	35,000,000
EU25	70.0	110	155,000,000

*(cf. Lauterbach, 2011; cf. Estif, 2012)

SPH-systems could cover 3.1% of the total energy demand in German industry. This considers a proportion of 30% for solar process heat and assumes that energy efficiency will increase (Lauterbach, 2011).

Table 2.8 shows the potential of solar process heat supply in the food industry, the dairy and brewery (with NAB) sector based on the following assumptions, as defined by Lauterbach (2011):

- process heat supply < 100 °C, space heating and hot water,
- reduction of energy demand due to efficiency measures, electricity for heat supply and available roof area 60%,
- solar fraction by 30%,
- specific collector earnings 445 kWh_{th} m^{-2} a^{-1}.

Table 2.8: Potential of solar process heat supply in the food industry, dairies and breweries*

	Solar process heat potential [GWh]	Solar process heat potential [GW]	Solar process heat potential [m²]
Food Industry	2,694	4.24	6,053,930
Dairies	383	0.602	860,650
Breweries + NAB	264	0.415	593,050

*(cf. Lauterbach, 2011)

The conditions for realising the potential of SPH-systems are generally auspicious. This is the case for the food industry in general, but also particularly for dairies and breweries.

2.6.2 SPH-system design and optimised solar process heat integration

Challenging the extensive use of solar process heat supply is its fluctuating availability due to varying solar radiation, seasonal as well as day/night cycles. Baniassadi et al. (2015) describe SPH-systems with storage to compensate for intervals low solar supply to meet the demand for solar heat and process heat. They also describe SPH-systems combined with conventional energy sources. A major challenge for both is an economically efficient system configuration. Considering the process characteristics of solar energy consumers, Baniassadi et al. (2015) aims to maximise the solar fraction of a defined system configuration and then optimise its economic efficiency. The optimised integration point of solar process heat need not have a negative effect on heat recovery and should minimise the use of conventional fossil fuels for backup heating. A case study by Baniassadi et al. (2015) was of a continuous distillation process that started with a pinch method for optimising heat recovery. This hypothetical process provides generally good conditions for a direct solar process heat supply without storage. The Baniassadi et al. (2015) procedure was used to analyse the process conditions and compare them to the heat supply conditions of the SPH-system. Solar heat supplies the process up to the first heat recovery stage. If there is further solar heat available, it is fed to the process after heat recovery. For a detailed evaluation of the energy supply from an SPH-system, a simulation is necessary. However, Baniassadi et al., 2015 based his scientific work on a specifically defined process with simplifications to find optimised conditions for SPH-systems, or for application of the pinch method for heat exchanger network design. The consequences of this approach is a gap between it and real world applications that prevents generalisation to guidelines for industry.

The approach of Frein et al. (2014) is the simple integration of an SPH-system to an industrial dyeing process in a Tunisian factory that faces the challenge of economic efficiency. Such a simple integration should prevent changes of the existing process and its infrastructure, and keep new investments low. The final SPH-system design preheats the hot water necessary for the process in storage without disturbing the existing steam heat supply. A simulation accompanies the design process. This includes validation of the simulation model of the dyeing process, the development of load profiles for the process and a detailed simulation of the newly designed SPH-system. The results of a study by Frein et al. (2014) show that the economic barriers imposed by sporadically cheap fossil fuels cannot be overcome for such a system without high subsidies. Frein et al. (2014) provided a scientific analysis that did not aim to provide a methodology for application by companies.

The operation of an SPH system should result in maximum capacity and performance (Quijear and Labidi, 2012). System design and integration of solar process heat in combination with other energy sources is therefore important in connection with the provision of heat to a complex process. Quijear and Labidi

(2012) combined the pinch method and exergy analysis for defining the problem processes at a dairy located in the Basque region. As dairy processes are batch processes with varying start and stop times, Quijear and Labidi (2012) used the TAM (Time average model) of the pinch method to determine the pinch point. TAM is simplified and needs less information but does not differ between direct and indirect heat exchange. The exergy analysis is applied to processes and solar thermal energy and should illustrate the decline of exergy. Background information provides a process analysis with a resulting process energy balance. After optimisation of the existing system, Quijear and Labidi (2012) prepared those systems for integration with solar heat. They vary the system size with solar fractions from 1.0 to 0.0 and compare the system efficiency and economy for the optimisation. Without simulation, and using fixed temperatures for a batch process with a limited time period, this seems a rough estimation. Quijear and Labidi (2012) do not completely analyse the waste heat (e.g. that from chillers or air compressors remains unconsidered). The optimisation of the SPH-system is with fixed parameters against an idealised background. The requirements of system operators or designers are neglected, which emphasises the gap between the concept and the real world.

Solar process heat systems can supply energy for various applications. One possibility is the energy supply for adsorption chiller. Best (2012) assessed the Agro-Food industry in Mexico to determine the potentials of solar cooling. A solar thermal system with Fresnel collector was designed to support cooling of an exemplary meat processing company. The case study analysed the maximum contribution of the solar driven part of the cooling system with simulations. Despite promising results, the designed solar cooling system (not implemented to the company) could not be operated economical. Best (2012) recommends therefore further investigation regarding a combined supply of cooling a heat by the solar process heat systems. This aimed to increase solar energy supply and improve economic efficiency. Atkins (2009) identified low-grade processes of the New Zealand food, beverage or textile industry that can be supplied with solar process heat. Challenging is the discontinuity of solar process heat supply and the connection with existing energy supply systems. The solution shall be a combination of data from the solar process heat system and data from the processes by doing a site pinch analyses. Atkins (2009) applied the resulting method at an exemplary dairy and milk powder producing company in New Zealand. The design and simulation study of the solar process heat systems aims to identify the most promising integration point of solar heat to the existing heat supply. Both, Best (2012) and Atkins (2009) analysed application variations of SPH-systems in the food industry. Completely different locations (Mexico and New Zealand) demonstrate the relevance of the technology for future energy supply. However, both did just design and simulations studies without the implementation of reals systems. Additionally, methodologies for energy engineers or other decision makers at companies have not been developed.

2.6.3 Industry specific concepts

Apart from pure energy efficiency, heat recovery concepts or the integration of solar process heat to the industrial heat energy supply, there are approaches that focus on green food companies. The superior objective is the minimisation of CO_2 emissions by reconfiguration of the energy and production systems. These industry specific concepts are described below.

Muster-Slawitsch et al. (2011) proposed a green brewery concept that aimed to demonstrate potential for the reduction of CO_2 emissions, with the ultimate goal of a CO_2-emissions-free brewery. The approach is the reduction of thermal energy consumption with increased energy efficiency (e.g. heat recovery or process intensification, combined with substitution of fossil fuels with renewable energy from biomass). To this end, they introduced a concept procedure with four steps. Table 2.9 illustrates the methods and intended results of each step. The data used to create the basis for the concept was provided by three breweries. Muster-Slawitch et al. (2011) used energy balances, energetic benchmarks or the pinch method TAM (time average model) as tools for the optimisation of the brewery batch processes. The concept of the heat supply starts with the integration of heat recovery but also changes the in-process technology to reduce thermal energy demand. Low-grade heat demand should be supplied with district heat, heat from existing CHP, heat pumps or by integration with SPH-systems. Finally, a biomass based heat utility should cover the remaining demand.

Table 2.9: Methods for green brewery concept*

Step	Example Method	Example Result
Data acquisition	On-site visits	Load profile of processes
Energy demand analysis	Thermal energy balance	Optimisation potential
Energy demand reduction	Cleaner production measures	Identification of savings due to technology change
Integration of renewable energy	Techno-economic evaluation for implementation of renewable energy sources	Concept for integration of renewable energy resources

*(cf. Muster-Slawitsch et al., 2011)

Muster-Slawitsch et al. (2011) found promising potential for reduction of thermal energy demand and CO_2 emissions at breweries, whereas the specific thermal energy demand is very different between breweries. The responsible staff often know about energy demand only from energy bills, and not about the details of energy consumption. Hence, another major finding was the necessity to increase the awareness of the brewery staff regarding the energetic behaviour of the brewery. The focus is on the maximum reduction potential of thermal energy and CO_2 emission. Therefore, the concept is based on measures that require substantial reconstruction of energy supply facilities and of the production processes and equipment. That means comprehensive interventions in existing structures. Willingness and economic possibility must be evaluated. Furthermore, the practicability of the proposed procedures (steps, methods and results) requires feedback from energy engineers, but this was not part of the concept.

Brunner et al. (2015) further developed the green brewery concept and proposed the GREENFOODS branch concept (Greenfoods, 2015), intended to achieve green production. They include additionally findings from other research (e.g. the SO-PRO project: Sopro, 2012). The concept was for application by SME's of the European food and beverage industry. It was proposed as an energy audit and energy management tool for the target group (the food and beverage industry). A broad audience, from energy engineers in companies, energy experts to energy suppliers but also the suppliers of process technology, were expected to use the concept. The objective of the improvements in energy efficiency, reduction of energy demand and saving CO_2 emissions was to foster the competitiveness of the European food and beverage industry. The company procedure is comparable to the green brewery (Table 2.9), with evaluation of the redesign. Results from the GREENFOODS branch concept are in the form of MS Excel-based support tools for energy balance or process analysis, guidance for the identification of funding as well as financing; and also a training course for energy audit experts (Greenfoods, 2015). As with the green brewery concept, this concept recommends comprehensive redesign and reconstruction regarding heat supply and processes. A concept such as Greenfoods should be for an industrial sector and needs to be very general. Consequently, it is less useful for application at companies and by energy engineers. A methodology for the application is therefore not focused, just as little as for the feedback of energy engineers. Finally, the concluding results are not yet available.

2.6.4 EINSTEIN tool-kit

The EINSTEIN tool-kit (Brunner C. et al., 2010) is a specific kind of efficiency guide for industries with comparatively high thermal energy demands at low and medium temperatures (< 400°C), as well as cooling demand. One target audience for the application is small and medium companies of the food and beverage industry. The tool-kit was originally developed as open source tool with funding from a European project (Intelligent Energy Europe – IEE) and is meanwhile a commercial product. It was intended to find users among energy auditors, consultants or researchers. These users should have comprehensive knowledge in energy issues for using the tool-kit. Hence, EINSTEIN is an expert tool for expert users (EINSTEIN, 2015).

As Brunner et al. (2010) describes, EINSTEIN is a combination of efficiency methodology and a software tool developed as an expert system with decision aids and guidelines. Its objective is an ‘integral approach to energy efficiency’ (Brunner C. et al., 2010) and combines several aspects. These include, among others, process integration, heat recovery (using the pinch method) and heat and cooling generation with several technologies. The EINSTEIN tool-kit consists of four phases as illustrated in Figure 2.23.

The first two phases of that procedure combine manual data acquisition with a consistency check and on-site analysis of the company. A questionnaire should be used to assist the data acquisition in the first phase. These two phases are comparable to the energy audit for the processes based on the DIN EN 16247 (2014) standard. They provide the data input to the EINSTEIN software tool but focus on thermal process energy demand. The analysis of electricity consumption is just on the company level.

As Figure 2.23 shows, the EINSTEIN software tool is mainly used in the third phase of the procedure.

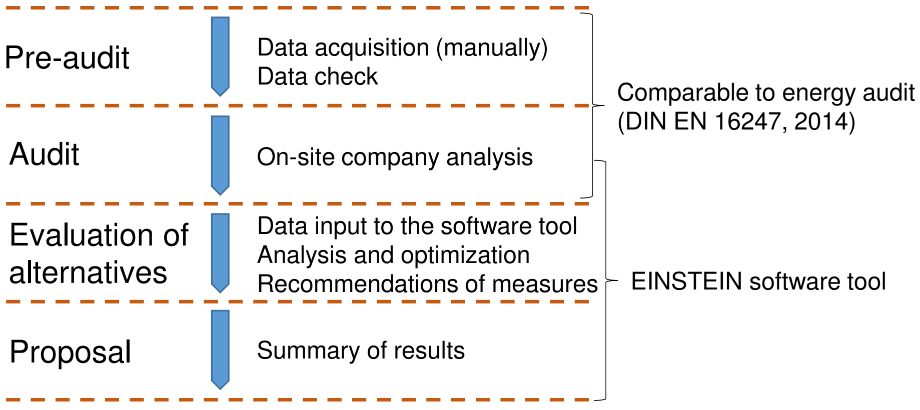

Figure 2.23: EINSTEIN procedure (cf. Brunner C. et al., 2010; cf. EINSTEIN, 2015)

However, it gets the data from the first two phases and passes the results to the fourth phase. Four interdependent modules form the software tool:

- module for data acquisition,
- module for the design a proposal for a new energy system,
- module for the evaluation of the proposal,
- module for the report (results).

The module for the reports represents the final fourth phase of the methodology and should provide a prepared result to the user.

The EINSTEIN tool-kit raises the claim of being a very comprehensive procedure for the optimisation of the thermal energy supply of a company, and that should provide energetic solution approaches. The verification of the EINSTEIN results of a company analysis is complex and needs expertise. Feedback from different users of the tool-kit is not available. That would be necessary to evaluate the useful elements of the tool-kit regarding its usability by energy engineers.

2.6.5 Planning and integration of solar process heat systems

A characteristic feature of SPH-systems in operation, as described in Section 2.6.1, is always the dominance of individual planning. This means less the configuration of the SPH-system, and more the efficient integration of the low-grade heat supply with other heat sources. Consequently, the expertise from planning, integration and commissioning is transferable to only a limited degree. Some research projects were intended to face deficiencies by the development of SPH-guidelines (Sopro, 2012; Schmitt, 2012; TU Wien, 2013). The objective was, therefore, focused on identification of general background facts regarding the conventional process heat supply and process heat consumers, concerning the integration of SPH-systems. Each of the following research projects had a specific approach to achieve this objective.

- Sopro (2012) analysed several industrial sectors (e.g. chemical, textile or food) in different European regions. Therefore, the results are more general and addressed not to industry and engineering companies but to suppliers of solar-thermal equipment and installation companies.
- Schmitt (2012) focused on German breweries and analysed energy relevant processes and applications. The result is a description of the processes, and an allocation to the brewery production areas (e.g. brew house). With this, the project was intended to determine suitable interfaces for solar energy integration.
- TU Wien (2013) analysed several branches of the food industry in Austria. The focus was on an exemplary optimisation of production processes. The improvement of the process technology and operation was the further

basis for shifting energy supply to renewable energy sources. Solar process heat was one among other options.

Important findings with regard to solar process heat integration can be summarised as checklists, on one hand, and recommendations of general procedure, on the other hand.

The checklists (Figure 2.24) provide criteria and should enable the decision makers of industry and planning companies to verify the potential for solar process heat integration.

Criteria	SOPRO (2012)	SCHMITT (2012)	TU WIEN (2013)
Process Temperature	< 100 °C	not specified	< 100 °C
Collector mounting area	> 50 m²	not specified	not specified
Collector orientation	south	not considered	not considered
Process energy demand	continuous production	analyse load profile	analyse load profile
	not specified	not specified	mainly between 30-120 °C
	summer > winter	not considered	not considered
	production also on weekend	not considered	production also on weekend
Storage	available area > 10 m²	not considered	not considered
Heat recovery	before solar energy	before solar energy	before solar energy

Figure 2.24: Aspects of Different Checklists

Figure 2.24 compares the criteria of the reviewed research projects (Sopro, 2012; Schmitt, 2012; TU Wien, 2013) and further illustrates their differences. For Sopro

(2012) and TU Wien (2013), for example, the process temperature should not exceed 100°C, but a limit is not specified exactly by Schmitt (2012). Schmitt (2012) and TU Wien (2013) do not consider the collector orientation. Hence, a complete comparison is impossible and no checklist can be evaluated as complete in the end. Finally, the defined criteria are very general and provide just indications.

In addition to the complete checklists, a number of recommendations have been given to describe and define the process from planning to integration of a SPH-system. As Figure 2.25 illustrates, there are also differences between the project results (Sopro, 2012; Schmitt, 2012; TU Wien, 2013).

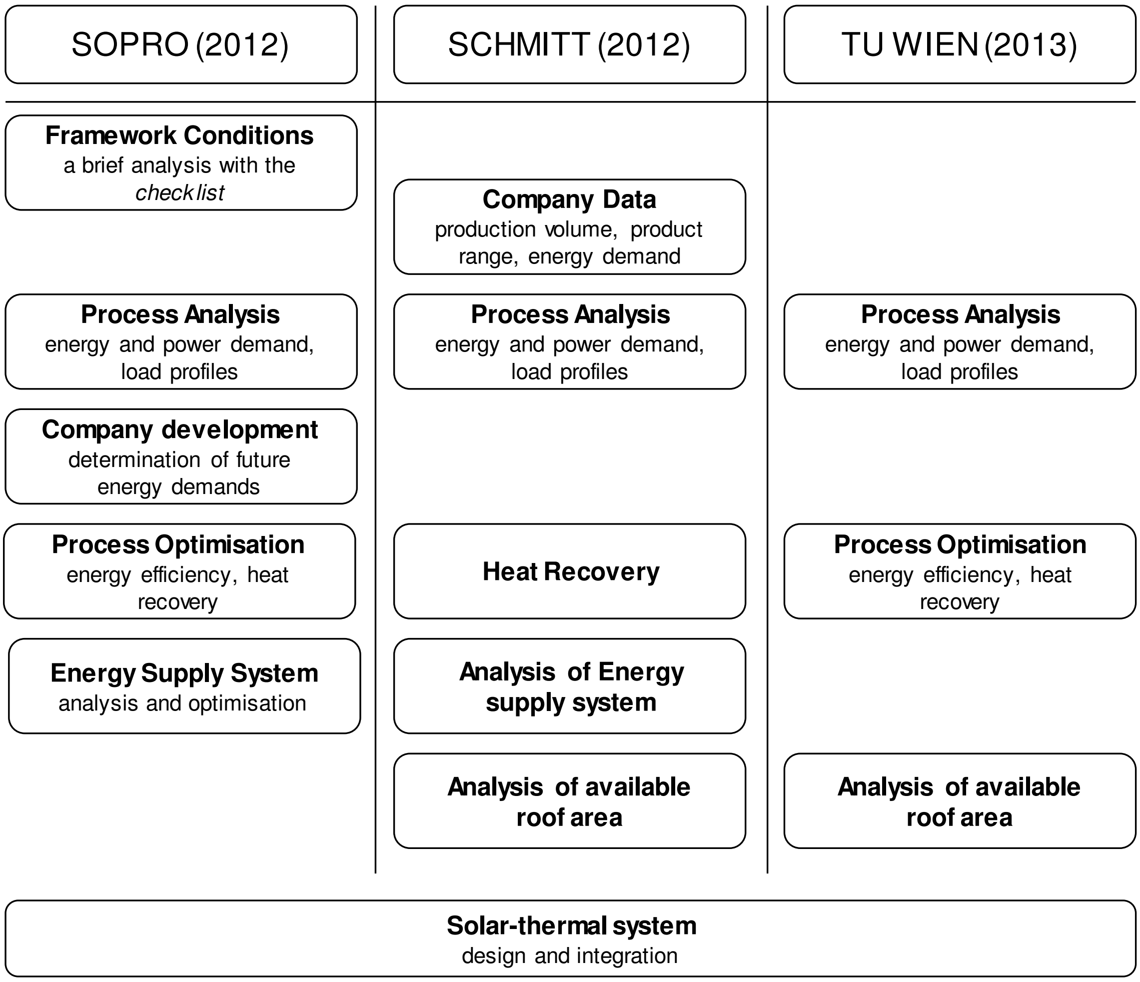

Figure 2.25: Recommendations

Some of the recommendations include content found in all projects (e.g. Process Analyses). However, ‘Company Development’, for example, is only found in the Sopro (2012) recommendations. Moreover, only Sopro (2012) gave rough figures on the economic efficiency of some demonstration plants. General economic feasibility studies are not included in any SPH guideline. Hence, an overall recommendation for economy is not available. The individual background and the objectives, as described before, is the reason for these differences. It illustrates also that there is no consensus for a methodology of SPH-system integration.

2.7 Investment in energy efficient technologies

It is essential to know the general motivations of the industry for their investments. Several studies have investigated the specific motivation for company investments in energy efficiency and energy supply technologies.

Aspects of major importance are the reduction of energy costs, but also important is company policy regarding corporate social responsibility. The energy costs depend on a global market influenced by a variety of factors. Hence, their development has limited predictability and involves certain risks. The motivation means to avoid economic risks but also to ensure competitiveness by control of energy costs. A voluntary commitment of saving energy and greenhouse gas emissions is the background of company policy. The motivation is often part of public relations and image building. Decision-makers responsible for the company energy systems are another important factor. The motivation and insight of such people is able to bring about changes affecting the company. The result is, in each case, an improvement of energy efficiency. About 92% of such activities are investments in technology for companies that own their energy supply systems. These are primarily investments in renewable energy technologies (pwc, 2015).

However, there are also obstacles to energy efficiency investments. The two most frequent reasons are lack of time and lack of capital. With the lack of time, companies describe limited resources of responsible staff and describe their core business as much more important than energy efficiency. One result can be higher energy cost to reach production objectives, which means ‘production first’ (i.e. before efficiency). This affects SMEs most of all. Many companies would invest in energy efficiency but need their capital more for production-relevant investments. Energy efficiency efforts fail when capital is too limited (Mie, 2015).

Nearly half of the companies select funding of energy efficiency as the most important for own investment (Eep, 2015). This would help to sustain liquidity but also to reduce amortisation periods and therefore the capital commitment. Many companies make use of consulting from energy experts to help find the best solutions. About 20% of such companies are not satisfied with the results, finding the recommendations too general or too superficial (Mie, 2015).

2.8 Findings from the literature review

The industrial sector uses large amounts of thermal energy at low temperatures, conditions which are suitable for solar-thermal applications (Section 2.1). Within some branches, like the food industry, the fraction of that low-grade heat grows to more than 40%. Processes at breweries and dairies are mainly at low-temperatures and are favourable for solar process heat (Section 2.2).

Despite promising energy saving potential, the number of SPH-systems in operation is still low. The technology is available and cannot be considered a real barrier. State of the art components (e.g. collector, storage) such as used for medium and large systems for domestic heat energy supply, indicate sufficient technical background. One reason for the low application of SPH-System could be the motivation for investments (Section 2.7). On one hand, companies point out increasing complexity that discourages investments in efficient technologies. On the other hand, adequate funding and more specific consulting would better support companies in achieving energy efficiency. However, it is very important not only to see best practice examples, but also to understand their technologies and implementation, as Peter Kraus (technical manager at the case study brewery) confirmed in a conversation on 18 July 2015.

The literature review and analysis in Section 2.3 to 2.6 approaches its aim to overcome existing barriers. Figure 2.26 classifies these approaches again in categories, as explained below.

Energy audits are based on standards and often legislative backgrounds. Such standards aim to support energy consuming companies in getting more insight into their own energetic behaviour. The focus is on analysis and documentation of energy data. The general procedures give just a rough structure, mainly for energy auditors, and leads to large variation in application results. The result of a good application of an energy audit can provide a general basis for energy efficiency, but does not equal the implementation of energy efficiency.

Energy efficiency not only contributes to the targets for saving energy and reducing CO_2 emissions specified in legislation, but is also important for the industry itself, to manage its energy demand. Experts can get general or information or specific information by industrial sector. Very little of this information specifically addresses energy engineers at companies. The focus is on cross-sectional energy efficiency that includes heat recovery (Section 2.5.3). These guidelines do not provide a methodology. The information on renewable energies is limited, especially about SPH-systems.

A lot of scientific work has been done on energy efficiency regarding heat recovery in connection with low-grade heat supply. The resulting procedures and methodologies focus mainly on appropriate processes. They demonstrate maximum potential using detailed simulation. This leads to a large gap between these and realistic applications. A translation of the results to form usable by energy engineers in companies requires comprehensive work.

A similar situation involves scientific work in the field of SPH-system design and solar process heat integration. Sometimes real world systems provide the background information for theoretical studies using complex tools. The research of SPH-systems focus not on specific locations but covers regions all over the world. Pinch analysis and simulation is often used for the definition and evaluation of maximum energy saving potentials. The results on this level are not for company energy managers.

Category	Reference	Audience / User	Focus / Objective	Characteristics	Analysis Results
Energy Audit	Standards (Chapter 2.4.1, chapter 2.4.2) e.g. DIN EN 16 247-1; ESOS	Energy Auditor Energy Consultant (Energy Manager)	• Data acquisition • Improve knowledge on energy demand • Documentation of basis data for energy efficiency	Background for legislation	• Minimum standard for all industries • Rough, general procedure • Different approaches → different results • Limited on analysis and documentation • Energy efficiency as task (no design recommendations)
Energy Efficiency	Guidebooks (Chapter 2.5.2, Chapter 2.5.3)	Experts Energy Consultant Energy Manager	• Illustration of efficiency measures • Compilation of mainly cross-sectional technologies • Industry sector specific	Recommendations: • Economic evaluation • Implementation • Tools and Funding	• Illustration of energy efficiency barriers • Missing consideration of EM feedback • Compilation of energy efficiency • No methodology • Limited regarding renewable energies
Energy Efficiency with Heat Recovery Low-grade heat supply	Scientific Methods (Chapter 2.5.4)	Researcher High level Experts	• Illustration of heat recovery measures • Background is low-grade heat supply • Integration in existing structures • (partially renewable energy)	• Methodology structure • Use of scientific tools (Pinch, simulation)	• Use of complex analytical (tools) • Detailed simulation studies • Demonstration of maximum potentials • Distance to real world application • Specifically application cases • Mainly impossible to convert into guidelines for industry • For researcher or high level experts • No consideration of EM (feedback)
Solar Process Heat Systems	Scientific / Research (Chapter 2.5.2)	Researcher High level Experts	• Implementation of SPH-system • Economic implementation • Background are real world cases	• Methodology structure • Use of scientific tools (Pinch, simulation)	
Solar Process Heat Systems	Guidebooks (Chapter 2.5.4)	System Designer Energy Manager	• Implementation of SPH-system • Assistance to audience / user • Increase SPH-system use	• Design recommendations • Nomogram	Missing aspects in each method (Chapter 2.5.4)
Branch Concepts	Green Brewery Green Foods (Chapter 2.5.3)	System Designer Energy Manager	• Minimisation of thermal energy demand • CO2-free heat supply • Energy efficiency and renewable energy	• Design recommendations • Tools (Pinch, simulation)	• Concepts for maximum potentials (only for a small number of companies) • Strong intervention in existing structures • Methodology is not in focus • Distance to company EM (no feedback from concept user)
Tool	EINSTEIN (Chapter 2.4.5)	Energy Auditor System Designer (Energy Manager)	• Expert Tool • Shall support Branch Concept (Background Green Brewery)	• Software • Energy audit • Optimisation recommendations	• Commercial use • Complex application (expert tool) • Verification of results needs expertise

Figure 2.26: Findings from the literature review

The SPH-guidelines of Section 2.6.3 show general facts about SPH-systems and their configuration. However, it is missing; first a comparison of competing heat sources, and second, the individual deficiencies missing from some aspect of the integration process (Section 2.6.3). The guidelines do not provide complete methodologies and are in some aspects insufficient, as now prepared. Feedback from applicants on usability is very important for a methodology design, and currently lacking.

The industry specific concepts provide an approach for minimum thermal energy demand with the lowest possible CO_2 emissions. This demands comprehensive redesign of existing structures and includes energy supply systems as well as production equipment. Hence, the application of such concepts requires not only expert knowledge in the specific industry sector but also such knowledge of energy efficiency and the whole range of energy supply systems. It is critical that complex redesign of the heat supply is complemented with a redesign of the process technology. Strong intervention requires comprehensive feedback on its acceptance by company decision makers and energy engineers, which is not available yet.

The industry specific concepts and their results were mainly background for the EINSTEIN tool-kit (Section 2.6.4). This was an attempt to integrate renewable energy sources into the optimisation of thermal energy supply systems. The result, however, is a complex software tool that requires expert knowledge, not only of many different technologies but also about optimisation and design methods regarding application of the tool, along with verification of the results.

A methodology focusing on the efficient integration of SPH-systems needs to include technical and energy relevant aspects. Each of the analysed standards, guidelines, industry specific concepts or SPH-guidelines within the literature review, can therefore contribute useful parts:

- Guidance for the analysis and documentation of energy demand and supply for a company with focus on process heat. This will support the company in understanding its energetic behaviour.

- Energy benchmark of the company with the analysis results combined with production figures. This is for definition of general potential savings.
- Analysis of heat recovery potentials to increase energy efficiency (saving energy and reducing CO_2-emissions).
- Analysis and evaluation of all available and competing heat sources. It is for an energetically useful energy supply and ensures sufficient integration of the defined heat energy consumers.
- Low-grade process heat distribution, can be an efficient heat supply for processes. This requires detailed process-analysis with definition of minimum low-temperature energy demand using methodological process analysis (e.g. pinch method).
- Structural conditions for collector mounting can be limiting. An analysis of buildings, combined with possible application of existing components (e.g. storage), is needed for configuration of the SPH-system.
- Development of a multivalent process heat system including heat recovery, solar process heat and conventional process heat, is for efficient energy supply to low-grade heat consumers.

All the steps towards an efficient energy supply, with heat recovery and solar process heat, must be arranged to form self-contained elements. Finally, these elements of a novel methodology must consider the completeness and detail required, in combination with helpful tools.

It is just as important to get feedback on the methodology, as it is to develop the methodology with sufficient procedures and tools. The literature review uncovered a deficiency in this aspect. A methodology is for the use of the defined audience and must take this audience into consideration. The focus is on the energy engineers at companies.

Figure 2.27 illustrates important aspects. The methodology for SPH-system integration with a low-grade heat supply (upper centre of the figure) represents the procedure with all the technological and energetic steps. On the right, there is a clear structure required for the application. Opposite, on the left, there are the elements and functions that represent the steps to an efficient heat supply with solar process heat. The application of information from case study is background for user feedback. This is the main objective of the development of this methodology.

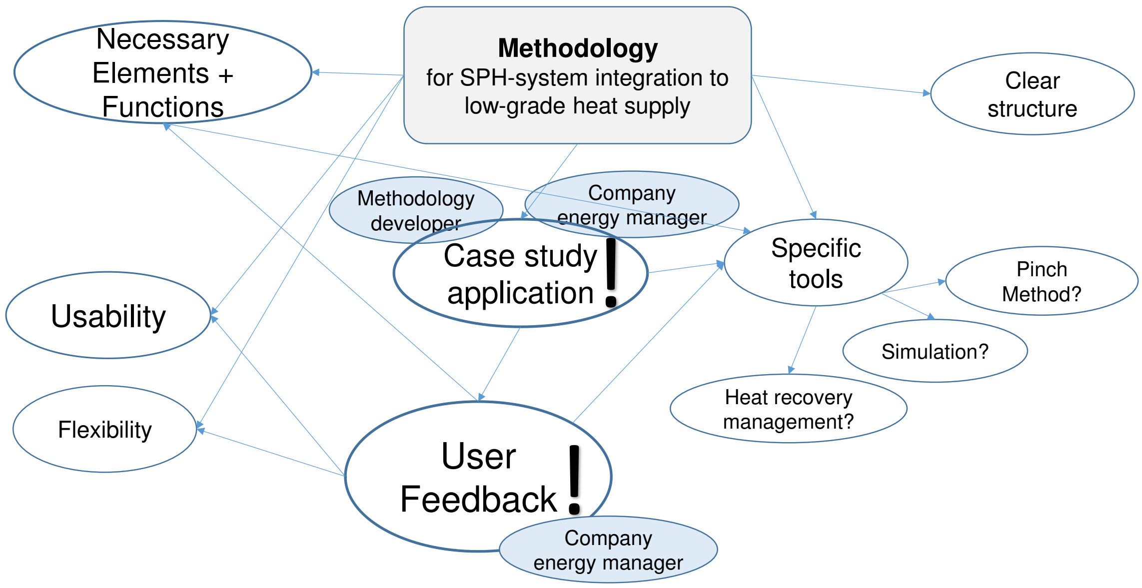

Figure 2.27: Outstanding unmet requirements for a methodology for SPH-system integration

Case studies enable a common application for development of methodology, with energy engineers to apply the methods. The feedback from energy engineers is essential for evaluation of the methodology elements, and also functions as specific tools. This results in available expertise at the companies, specifically the expertise necessary for application. It also enables conclusions about the necessity of company support from external system designers. Finally, the feedback summarising such efforts provides important background about the overall usability of the methodology by the broader audience of industrial energy engineers.

2.9 Research question

The introduction and literature review present information on industrial energy supply and energy efficiency. SPH-systems are usually not specifically included in energy efficiency guides and the specific SPH-guidelines show deficiencies. The detailed scientific work highlights gaps between such concepts and real users. This is a fact that needs to be considered because SPH-system implementation also depends on the motivation driving investment and demands well-conceived process heat solutions that are convincing to a company. Therefore, energy efficiency and SPH-System integration need a structured procedure applicable by energy engineers. This procedure should consist of compatible functions (Section 4.2) and lead to answers to the research questions below:

> *'What are the essential functions of a structured methodology for the design and implementation of solar process heating systems?'*
>
> *'Will this methodology be able to provide a platform with good usability and flexibility to support energy engineers in the design of cost-effective solar process heating systems?'*

3 Research Method

The research in this thesis consists of two parts. The first part is the development of a methodology. Existing knowledge of a specific domain – analysed using information from the literature review (Chapter 2) – is complemented with new aspects to provide a novel and applicable procedure. The methodology itself represents the theoretical part and needs to be tested. This real world test is the second part of the research and represents its practical aspect. Such a sequence of first theoretical development and then practical application is a deductive approach in research, and the most common way (Bryman, 2012). In contrast, an inductive approach would mean first developing a practical part, with theory derived from it afterwards (Figure 3.1).

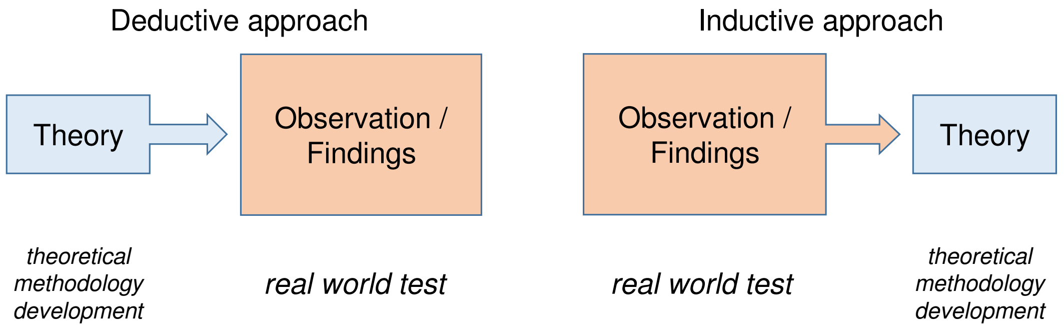

Figure 3.1: Deductive and inductive approaches (cf. Bryman, 2012)

The deductive approach was chosen, because several energy efficiency guidelines and SPH-guidelines, provided a comprehensive background for the methodology (Section 2.4.2). This enables development of a theoretical methodology independent from industry, and later test of it in the real world.

Using the real world as basis for the research is very helpful in this connection. Robson (2011) explains the importance of this approach for applied research and provides topics of current interest. This research was therefore carried out considering the group of prospective users.

3.1 Case study

Two companies supported this research. Hence, the decision was already made at an early stage to test the methodology using case studies. The use of only two cases allows the possibility of comprehensive and detailed scenarios. This research method ensures application of the methodology in the real world and as described, before an effective exchange of information with energy engineers and system designers as prospective users.

In general, case studies enable investigation of complex phenomena. They are, alongside surveys and experiments, a major tool for research and are particularly suitable within a real world context (Yin, 2014). Case studies give research the potential to investigate a defined system in depth (Miller and Salkind, 2002). Yin (2014) distinguishes single-case and multiple-case designs. In particular, the results from single-case studies need critical analysis comparable to single experiments, because a large number of comparable cases is not available. Single-case studies need a more common design, if the results shall be transferable (Yin, 2014). The defined test environment may not be unique. In this regard, Gerring (2007) recommends choosing a ‘typical-case’ and describes therefore a base-case with typical characteristics.

With two exemplary case studies in this research, it is a kind of single-case. Both of the companies chosen for the studies represent a base-case. In one case, the brewery is an SME with a production volume representative for an important category of the brewery branch in Germany: those with mainly regional markets. In the other case, the dairy represents larger companies in the category of modern and progressive milk processing companies in Germany: those with a large market share nationally, and also with international markets. Additional comparison is intended of the results between the size categories.

3.2 System analysis

The implementation methodology for SPH-systems includes analysis of the energy supply and energy distribution of a company. This analysis is an essential part of the case study for the methodology test.

Energy supply and energy distribution in this case are systems. Among others, Solding (2008) figured out that the overall goals, the environment and the components of a system are the most important aspects. Krallmann (2013) began analysis of a system with an exact definition of the boundaries. The complexity of a system depends on its number of components and no component within the system is independent (Krallmann, 2013). This is also a measure of the degree of individuality.

Schieferdecker (2007) defined a connection of components as well as inputs and outputs for systems (Figure 3.2). This simplification enables system analysis with various input (e.g. raw material for production and energy) and output (e.g. products and emissions). With a combination of production and energy, an exact definition is therefore a major task within system analysis. Besides components, input, and output, Schieferdecker (2007) pointed out the definition of specific key figures needed for the system evaluation.

Figure 3.2: System description on a macro level (cf. Schieferdecker, 2007)

Finally, the system defined, provides the background for development of simulation models.

3.3 Model development

The static analysis of systems provides useful information about their overall conditions. The analysis of their dynamic behaviour, however, requires the simulation of subsystems or of the entire system. The background for a simulation is the development of system models.

Stachowiak (1973) describes a model as a limited reflection of a real world system. This enables the researcher to focus on important aspects of a system and to simplify it. This simplification is recommended to get efficient system models. However, the model must not be completely separated from the real system (Zirn and Weikert, 2006). A good system model should always use this background to represent a part of the real world.

The development of system models assumes detailed knowledge gathered with system analysis. Beside component data, this means data about input and output. The process of development is not a single event but in most cases a cycle with several loops. Glotzbach and Ament (2014) defined a system modelling cycle. It illustrates data acquisition from the real world system to understand the system behaviour and to transfer it to the model. An optimisation of the system model takes place with several simulation runs. A continuous comparison of simulation results with data from the real system is the basis for that optimisation. This procedure ensures that simulated results parallel results that would occur in the real system.

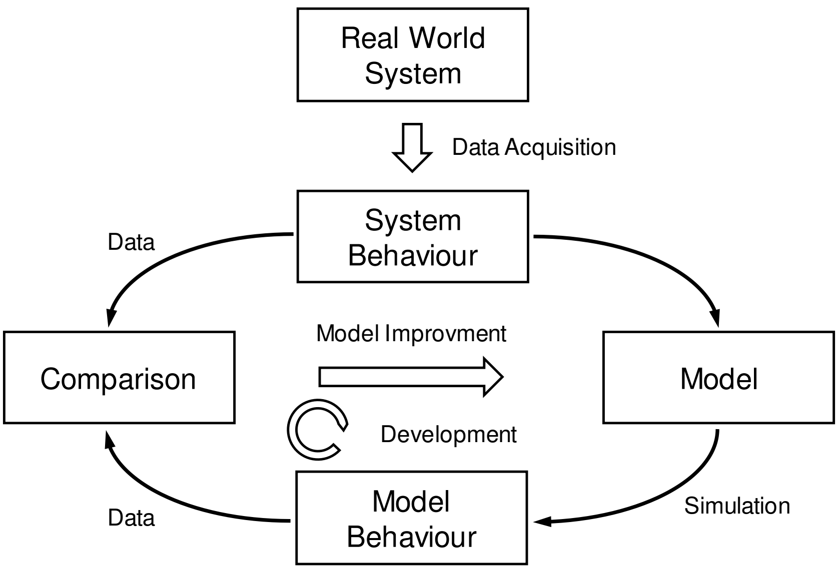

Figure 3.3: System modelling cycle (cf. Glotzbach and Ament, 2014)

4 Methodological system development

This chapter describes the development of the methodology for the integration of an SPH-system with a conventional process heat supply. It takes up the findings of the literature review and illustrates in Section 4.1 the main objectives of the methodology. An important aspect in this connection is the prospective user. Section 4.2 deals with configuration of the methodology structure and explains the background. Section 4.4 presents the defined and necessary steps to achieve an efficient low-grade heat supply supported by solar-thermal heat.

4.1 Objective and users

The main objective of the methodology is a structure for efficient integration of SPH-systems with the conventional process heat systems used in industry. Considering this, the energetic focus is on low-grade process heat and related distribution systems. The definition of efficient means energy efficiency regarding low-grade process heat supply and saving fossil fuels. Heat recovery is therefore a main aspect. Finally, the objective is to integrate the SPH-system considering its economic background. This methodology is intended to support the industry to comply with legislative requirements, but its application must also be able to support the self-defined goals of the companies, such as:

- Reduce the consumption of fossil energy for process heat supply.
- Save CO_2 emissions by decreasing fossil energy demand and use SPH-systems to substitute for fossil fuel energy.
- Control energy costs.

Two groups of users (Section 4.5) are the focus of the methodology development. Energy engineers in industry will operate SPH-systems. It is necessary that companies develop their own knowledge of their energetic behaviour. This is essential for informing decisions about company strategy for planning future energy systems, and relates more to SME’s than to large companies. Hence, they need usable methodologies that support their work. System designers from planning companies provide consultation to those in industry. They should use knowledge about the companies and combine it with their own expertise to develop innovative solutions. This expertise is defined as broad knowledge of various technologies and the possibility of using specific planning tools (e.g. simulation). Therefore, both groups must use their individual knowledge in complementary fashion.

Solar process heat is a technology that cannot supply all process heat demand; thus, it is limited to specific industries (Section 2.1). The literature review (Section 2.2) found that the food industry, particularly breweries and dairies are promising for SPH-system operation. Hence, the development of the methodology was adapted to these branches of the food industry with its specific conditions:

- Thermal energy dominates energy consumption of production processes and other applications.
- This industry sector needs large fractions of its process heat at low temperatures (< 100 °C).
- Thermal energy demand remains steady during the year and production is not typically interrupted.
- The production processes are mainly discontinuous and batch processing is characteristic.
- The company buildings provide enough area usable for mounting solar thermal collectors.

4.2 Methodology design process

This section describes the methodology design process for a better understanding to the reader. That design process results in the final methodology structure as presented in section 4.3.

The flowchart in Figure 4.1 illustrates the methodology design process with the steps (1) – (9). Background for the methodology structure is an analysis (1) of existing methodologies guides and research within the literature review (section 2.4 to section 2.6). This results in a draft of the methodology elements (2). A second analysis (3) is necessary for a redesign the methodology draft with focus on the functions (4). This is basis for decisions and initial point to the case studies (5). The cooperation with the energy engineers from the case study companies before the methodology applications allows a detailed view on their work: e.g. handling of energy data, methods and tools for data analysis. The findings of these discussions are input for a further methodology redesign (6) focusing on functions and tools. The resulting methodology structure is used for the case study application (7) as described in chapter 5. The methodology application is in close cooperation with the energy engineers. The feedback (8) of them is the final input for the completion of the methodology structure (9).

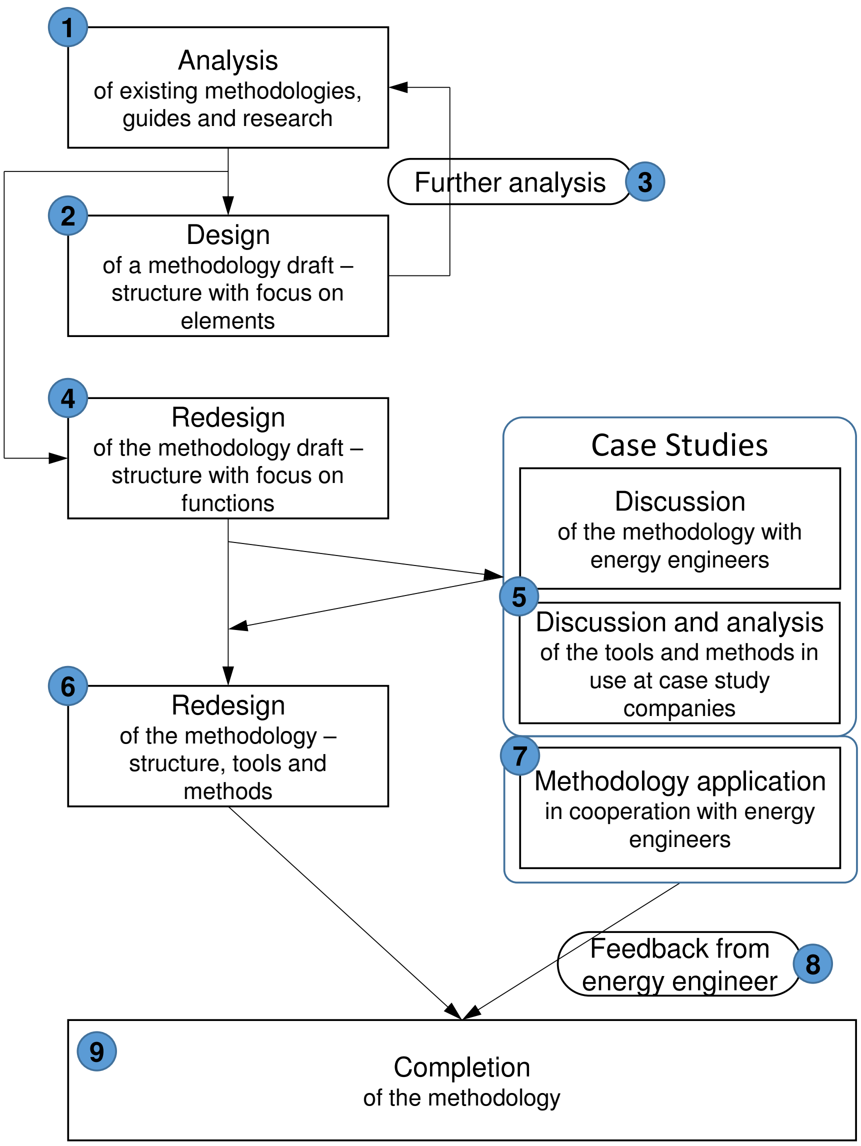

Figure 4.1: Methodology design process

4.3 Structure of the methodology

The literature review in Chapter 2 provided several categories of background information. Important findings included existing guides for energy efficiency and SPH-guidelines, but also scientific work and industry specific concepts. The analysis, particularly of the SPH-guidelines in Section 2.6, identified different gaps regarding a complete methodology towards solar process heat integration. One aspect almost completely missing is the integration of the user audience with the development of methodologies. However, this is essential for usability. With the background of the existing information, this novel methodology aims to close the gaps and provide users a guide for design and implementation of SPH-systems.

- The category energy audit (Section 2.4) is the background for analysis of a company's energy consumption. Such tools help to manage energy supply and distribution better, and also to introduce this topic into company policy. This makes energy subject to long-term attention and requires action from responsible energy engineers within the company.
- The category guides for energy efficiency (Section 2.5) supports the industry with energy efficiency and includes all forms of energy. They are, in most cases, a compilation of various measures and 'consult' (advise) the industry in general, but not industrial sectors, about this topic. In addition, the scientific work available presents barriers and approaches for the evaluation of energy efficiency measures.
- The category solar process heat systems (Section 2.6.2 and 2.6.5) for SPH-systems, already focuses on promising industry sectors. Low-grade energy supply and concepts for such systems are discussed.
- The category industry specific concepts in Section 2.6.3, proposes a comprehensive redesign of heat supply and process technology. However, the procedure for providing the concepts gives useful background for the analysis and optimisation of heat supply systems.
- In addition to the information categories, are tools for system simulation that are very helpful for planning and configuration. The simulation enables analysis of the dynamic behaviour of entire systems regarding energy

consumers and energy sources. Detailed knowledge of the system and comprehensive data input about it are necessary. This is an essential aspect of the implementation of an SPH-system.

The basic structure of the methodology is formed with elements that are derived from the categories above. Each element exchanges information with the others but should be usable independently. Figure 4.2 shows the order of the elements: energetic analysis, energetic optimisation, solar-thermal system integration and simulation.

The functions divide each element into several activities. A function therefore represents the specific tools or measures necessary to reach intermediate results. The assignment of these functions to each element constitutes an additional procedure.

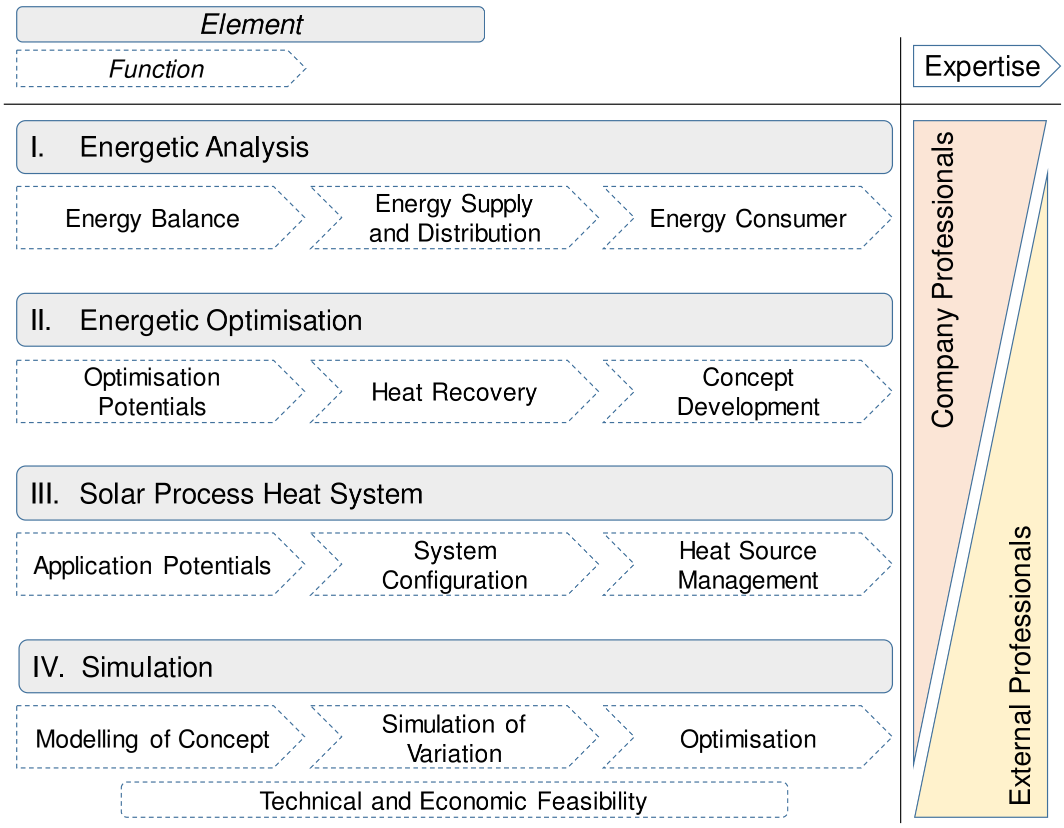

Figure 4.2: Structure of the proposed methodology

The methodology is designed for energy engineers and system designers (Section 4.5). The figure shows, therefore, the allocation of both to each element and represents the required expertise. The responsibility of energy engineers decreases with each element and increases for system designers. The indication of overlapping expertise emphasises the necessary cooperation.

4.4 Description of the methodology

This chapter gives a brief description of the methodology. It clarifies the structure of the elements to the reader and illustrates the meaning of the functions as developed in Section 4.2. In addition, the allocation of the responsibilities of energy engineers and external system designers will be explained. This description is complemented in Section 5.1 to 5.3 with the application that guides readers through the methodology and the presentation of tools with exemplary results in the case studies.

4.4.1 Energetic analysis

The basis of the methodology is a comprehensive company analysis with focus on energy consumption. CO_2 emissions and production figures complement the company analysis. The approach is a top-down method from a holistic view, towards a detailed analysis of processes and applications of energy consumers.

'Energy balances' is an essential tool for company analysis regarding fuel and electricity consumption. This tool enables illustration of the current and previous status of the company energy consumption, as well as of the resulting CO_2 emissions. A definition of balance periods and balance area (e.g. the production site of a company) ensure comparability. The energy balance is the basis for development of specific key figures. A key figure is a combination of a production quantity and an energy demand for the same period. Key figures are an energetic benchmark for other companies but are also useful for control of the self-defined goals of a company. Table 4.1 summarises the results of this function.

Table 4.1: Results of the function ‘energy balance’

Result	Description
Energy balance	Focus on fuels and electricity; defined periods and area
Emissions balance	CO_2-Emissions; derived from fuel and electricity consumption
Specific key figures	Based on energy balance and production quantity

‘Energy supply and distribution’ analysis, with focus on process heat, provides the energy supply units and the energy distribution networks. It starts with the energetic parameters of all the energy supply units and illustrates characteristic parameters (for example, heat capacity or supply temperature). This part of the analysis also includes cooling systems and pressurised air systems because these are potential sources of waste heat. The energy distribution networks depend on the characteristics of the energy supply units. Energy consumers provide further configuration parameters for the energy supply. The energy data from the distribution networks are summarised in the network energy balances, and illustrate only the specific form of energy distributed. Table 4.2 summarises the results of this function.

Table 4.2: Results of the function ‘energy supply and distribution’

Result	Description
List of energy supply units	Performance characteristics of the technology
List of energy distribution networks	Supply units; performance characteristics; connected consumers
Network energy balance	Energy balance with the specific form of network energy

The analysis of ‘Energy consumer’ is on the most detailed level of energy consumption and completes the energetic analysis. It distinguishes single consumer and consumer groups. An energy consumer represents a production process or a production supporting application. Consumer groups are several processes connected to the same distribution network, all supplied with the same form of energy. Consumer characteristics: heat capacity demand, supply temperature, total energy demand and duration of the process, form the basis of the analysis. These characteristics provide input for optimisation, as well as for the SPH-system configuration, and complement the load profiles. The load profiles illustrate the dynamic behaviour of energy consumers. This is useful additional information, because most energy consumers in the food industry represent discontinuous processes with varying heat capacity. Table 4.3 summarises the results of this function.

Table 4.3: Results of the function 'energy consumer'

Result	Description
Energy consumer	Production process and characteristics; form of energy supply
Consumer group	Definition of group characteristics; form of energy supply
Load profiles	detailed data of temporal energy demand

A completed energetic analysis illustrates the current energetic status of a company and is basic knowledge needed for the optimisation. This is the most comprehensive part of the methodology and should be mainly the responsibility of the energy engineers.

4.4.2 Energetic optimisation

Energetic optimisation is focused on energy supply and distribution of process heat. On the one hand, its objective is to save energy and emissions via the implementation of energy efficiency measures for the process heat supply. On the other hand, it aims to configure a platform for the integration of a SPH-system.

The 'optimisation potentials' give indicators for energy saving possibilities. The general potential comes from the energetic benchmark compared with other companies or the industry branch. This helps a company to define its own goals for future energy consumption. More company-specific energy saving potentials arise from the energetic analysis. The task is to identify suitable measures for energy saving and define real optimisation potentials. Regarding SPH-system integration, the focus is on low-grade energy supply. The defined potentials should also be preparation for the following function, 'heat recovery'.

Table 4.4: Results of the function 'optimisation potentials'

Result	Description
Energy saving potentials	General from benchmark; company specific with energetic analysis
Energy saving measures	Illustration of measure; saving potentials

The main function of the energetic optimisation is 'heat recovery'. Using waste heat provides very promising potential for saving fuels used for the process heat supply. It can substitute for fossil fuels and reduce CO_2 emissions. Heat recovery in the food industry refers to low-grade energy. This will be important regarding the later configuration and integration of SPH-systems. The earlier energetic optimisation has identified all the waste heat sources and a detailed analysis now completes the characteristics. This includes waste heat potential, waste heat capacity, source temperature and temporal availability. A comparison of characteristics for waste heat and energy consumers indicates the useful waste heat. This comparison provides an additional assessment of waste heat integration with the low-grade energy supply. Table 4.5 summarises the results of this function.

Table 4.5: Results of the function 'heat recovery'

Result	Description
Heat recovery measures	Waste heat source; waste heat potential
Heat recovery evaluation	Characteristics of waste heat
Heat recovery integration	Possibilities of waste heat use

The concluding function of the energetic optimisation is 'concept development'. It aims to configure an energy-efficient low-grade heat supply for the implementation of a SPH-system. In addition, the developed concepts provide parameters for the SPH-system design. The existing energy supply and distribution systems identified during the energetic analysis form the basis of the concepts. The first objective of the concept development is to optimise the conventional energy supply in relation to the distribution system, and then to add the integration of heat recovery. The second objective is the definition of the network parameters. These parameters need to be well defined, not only for the connected energy consumers, but also for the solar-thermal heat supply. Table 4.6 summarises the results of this function.

Table 4.6: Results of the function 'concept development'

Result	Description
Low-grade energy supply system	Basis concept; integration of waste heat
System parameters	Input for the SPH-system design

The resulting energy supply concept of the optimisation is the basis for the solar process heat supply. It should provide suitable integration points for the SPH-systems and provide the energy demand that must be provided with solar process heat. The energetic optimisation is largely in the area of responsibility of the energy engineers. Support from external system designers should extend the discussion and evaluation of promising optimisation measures.

4.4.3 Solar process heat system

The integration of solar process heat is the essential part of this methodology and starts with the system configuration. Its aim is to design an efficient and simple system combining the conditions of the company buildings as well as the energy supply and distribution.

A company-specific 'application potentials' analysis gives the energetic and technical restrictions. Two aspects determine the potential. One is the energetic parameter from the concept development. This initial factor is the energy demand of the distribution systems and its energy consumers that cannot be covered with waste heat. This energy demand represents the main design parameter for the SPH-system. The second aspect is the area available for the mounting of a collector, and is of major importance. This requires a comprehensive and detailed analysis of all the areas atop company buildings. The result of the application potential analysis is one energy-limiting factor and one limiting factor for the collector area. Both give the maximum size of the SPH-system (Table 4.7).

Table 4.7: Result of function application potentials

Result	Description
Energetic potential	Maximum solar-thermal energy supply
Technical potential	Maximum collector area

The function ‘system configuration’ deals with the design of the SPH-system and its dependence on the optimised concept for low-grade heat distribution. It starts with the system components and focuses on heat storage and collectors. The volume and charging system are essential configuration parameters for the storage. The selection of a design, connection and orientation are configuration facts for the collector. The system hydraulic combines all components into a complete SPH-system. It determines the mode of operation, the number of cycles and the mode of frost protection. The location of the system must be considered in relation to frost protection and orientation of the collector. The final objective is an SPH-system concept with the highest possible specific collector benefits. This is essential for operation that is economically efficient, and also for the substitution of fossil fuels and saving CO_2 emissions. Table 4.8 summarises the results of this function.

Table 4.8: Results of the function ‘system configuration’

Result	Description
System components	Collector design, area and orientation; storage design and volume
System hydraulic	Connection of the components; mode of operation
System concept	Complete concept for the implementation

The function ‘heat source management’ provides for an optimised combination of all available heat sources. The maximum energy supply of each source is the focus of this management. According to the definition of low-grade heat supply used with this method, this function is intended to use several similar heat sources to save fossil energy. Supply temperature, heat capacity and availability of the heat sources may overlap and temporarily provide more energy than actually used by the energy consumer. The discontinuity between many waste heat sources and – dependent on irradiation – variation in solar process heat, are the reasons. Thus, heat source management provides a matrix for energetic evaluation. A useful priority is determined for all heat sources, with the objective of achieving the best energetic use. Table 4.9 summarises the results of this function.

Table 4.9: Results of the function ‘heat source management’

Result	Description
Evaluation matrix	Parameters for heat source evaluation
Heat source analysis	Priority list of available heat sources

The configuration of the SPH-system and its integration with the optimised low-grade heat supply completes the conceptual development for the low-grade heat supply. The following system simulation can be done using the results from this element. The SPH-system configuration requires the expertise of an external system designer. Energy engineers support this part of the method with data input (e.g. for analysis of available collector mounting area).

4.4.4 Simulation

Simulation is a useful tool for testing concept configurations and verifying the energetic results. Simulations enable analysis of the dynamic behaviour of system components and optimisation of the configuration. This is important regarding the solar-thermal component and its contribution to the overall results. Modelling and simulation support not only the energetic optimisation, but also the detection of configuration errors.

The ‘modelling of concept’ is the first function of the simulation element. Tools with a high degree of individual modelling opportunities provide the most promising conditions. Objective is the development of system models close to real systems. Concepts from energetic optimisation (Section 4.4.2) and from solar-thermal system integration (Section 4.4.3) provide the background for modelling. The simulation model consists of exchangeable components suitable for individual parameterisation. Those components can be configured to form several system model variations and facilitates the optimisation. In addition, the system model works with real data input (load profiles) from the energetic system analysis. A simulation study of the developed system models, and analysis of the simulation result, completes the function modelling of concepts. Table 4.10 summarises the results of this function.

Table 4.10: Results of the function ‘modelling of concept’

Result	Description
Modelling of components	‘Toolbox’ of individual configurable components
Modelling of system variations	Complete system models ready for simulation
Simulation	Evaluated results of system simulation

The function ‘simulation of variations’ is the basis for optimisation. The system models from the previous modelling enable creation of variations with low reconfiguration effort. The objective is the optimisation of the energetic performance of the SPH-system. The waste heat supply must not be negatively affected. One approach is variation of the heat source order. The aim here is to verify the defined heat source priority from heat source management and optimise it if necessary. The simulation enables consideration and analysis of the dynamic behaviour of the heat sources. The second approach is sensitivity analysis of the SPH-system. This includes variation of system parameters (e.g. collector orientation or storage volume) with the goal of increasing the specific collector earnings. Table 4.10 summarises the results of this function.

Table 4.11: Results of the function ‘simulation of variations’

Result	Description
Heat source order	Reconfiguration of the heat source priority
Optimised SPH-system	Sensitivity analysis; optimisation of system parameters

The ‘optimisation’ combines the findings of the simulated variations with the basis configuration of the system models. The objective is concept configurations with the lowest possible fossil fuel consumption. Hence, energy supply with heat recovery, connected with an efficient solar-thermal component, reaches a maximum. The optimised concept is the final background needed for an update of the energy balance for the company, and for the low-grade energy distribution. It illustrates the energy and CO_2 emission savings possible via this concept.

Table 4.12: Results of the function 'optimisation'

Result	Description
Optimisation measures	Evaluation of optimisation results
Optimised system concept	Configuration of the optimised system concept; maximum heat recovery and solar process heat at minimum fossil energy demand
Energy Balance	Update of the energy balance; energy savings; reduction of CO_2-emissions

The result of the system simulation is an optimised system concept with a maximum use of waste heat and an integrated SPH-system. The energy balance from the energetic analysis is used for the concept analysis. This enables a comparison to the initial system configuration and figures out energy savings and a reduction of CO_2-emissions. A technical and economic feasibility evaluation of the SPH-system completes the concept development. Simulation of the energy supply systems require detailed knowledge. Such expertise is mainly limited to external system designers. Energy engineers can support the simulation process with data input and the evaluation of simulation results.

4.5 Methodology application by energy engineers

The methodology is for two groups of expert personnel (Section 4.1). System designers from planning and energy consulting companies are one group. They have comprehensive expertise on industrial energy supply and distribution systems. Furthermore, system designers are independent from specific system technologies and are able to consult different manufacturing companies to gain objective benefits for the client. This expertise also includes design and implementation of energy systems.

Energy engineers from the manufacturing companies are the other group of users and the most important regarding application of methodology. The methodology supports their work as decision makers, or when preparing others to make decisions at companies. It must be assumed that the expertise of energy engineers differs from that of system designers. With the background from the definition and preparation of the case studies (Section 5.2 and 5.3), a further distinction should be made between two categories of energy engineers.

The first category of energy engineers is specified as ‘part time’ energy engineers (PTEE). Characteristic of this group is that energy issues of the company are not their main area of responsibility. At the brewery, the energy engineer is first production manager. This limits his available time regarding energy matters and can lead to limited expert knowledge. Hence, this group of energy engineers require more support from external system designers. As Figure 4.5 illustrates, this support can be necessary from the first element in the methodology for energy analysis, on.

The second category of company engineers is specified as ‘full time’ energy engineers (FTEE). Characteristic of this group is that energy issues of the company are their main area of responsibility. The dairy maintains a department exclusively for energy issues of the company. The staff have detailed and comprehensive expert knowledge that is sometimes similar to that of external system designers. As Figure 4.5 illustrates, energetic analysis and energetic optimisation are their responsibility and are part of their basic knowledge. This expert knowledge is often focused on the energy requirements of their specific industrial sector. Hence, FTEE also require support from external system designers, but for a later element of the methodology.

Figure 4.3 Summarises the most important aspects of the expert definitions.

Expert	Works for	Description	Abbreviation
System designer	Planning and energy consulting companies	• Energy engineer for industrial energy supply and distribution systems • Independent from specific system technologies • High level of specific expert knowledge	SD
Energy engineer (full time)	Manufacturing companies	• Responsible for energy supply, energy distribution and production equipment • Main focus is on energy issues of the company • High level of industrial sector expertise	FTEE
Energy engieer (part time)	Manufacturing companies	• Responsible for energy related issues of the company among others (e.g. production planning, personal planning, maintenance activities) • Main focus is not on energy issues of the company • Low to high level of industrial sector expertise	PTEE

Figure 4.3: Definitions of methodology users

The different backgrounds of expertise also affects the application of the methodology. System designers have, in contrast to the energy engineers, the necessary expertise to use the methodology. Hence, it is expected that they could use all tools and measures in Figure 4.4 to reach the results for each element.

Element	Tools, Methods and Measures	
Energetic Analysis	• Energy balance • Specific key figures	• Energetic benchmark • ES&D network analysis
Energetic Optimisation	• Pinch Analysis • Heat source management	• Energy balance • ES&D network concept development
Solar Process Heat System	• Roof evaluation • Design standards for solar-thermal system	• ES&D network concept development
Simulation	• Simulation tool • Concept based system modelling	• Sensitivity analysis • Energy balance
Evaluation of SPH-System	• *Standards for economic evaluation*	• *Technical feasibility*

Figure 4.4: Methodology elements

The described effect of expert knowledge needs a further distinction for PTEEs and FTEEs. These levels of expertise are described in Figure 4.5. This figure includes consideration of the increasing expert knowledge needed for each element, as illustrated by the structure of the methodology in Figure 4.2 (Section 4.2). However, the figure also includes the different responsibilities of PTEEs and FTEEs.

The application of the methodology by energy engineers not only affects the energy efficiency of a manufacturing company and help to implement SPH-system technology, but also increases the awareness of energy demand and company-specific energy behaviour. An important side effect, therefore, will be an enhancement of company expertise regarding energy issues. Figure 4.5 compares this with the level of expertise, and the expected effect on expertise, as the methodology is applied.

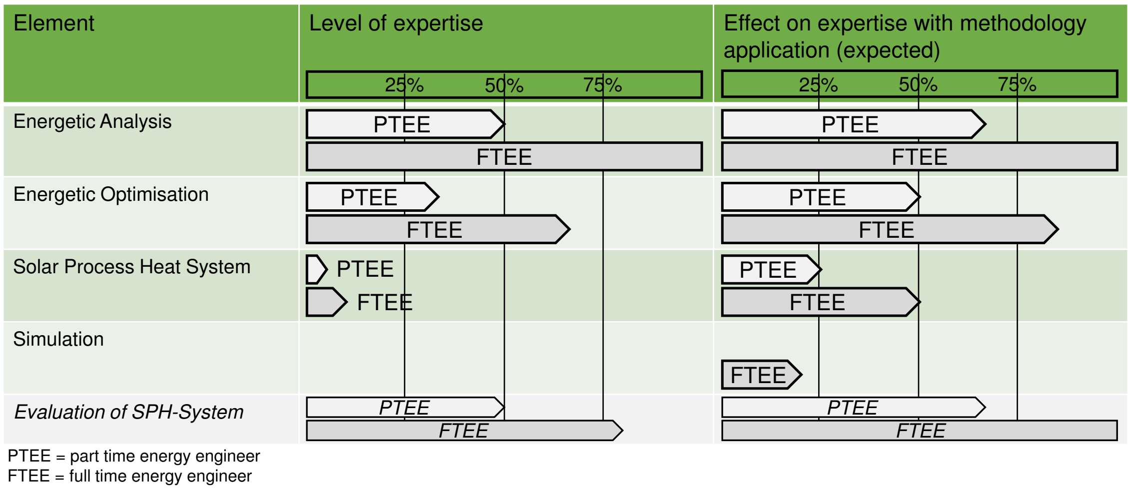

Figure 4.5: Expertise level and effect with methodology application

The application of the methodology using the case studies in the following chapter (Chapter 5) was carried out in close cooperation with the energy engineers. The feedback on their application of the method is therefore an important part of the case studies. This shall support verification of the general usability of the methodology as a whole, and of the usability of the individual tools and measures of the methodology.

5 Case studies

This chapter discusses the findings produced through application of the methodology presented in chapter 4 to selected case studies (identified in section 3.1). Section 5.1 therefore first outlines application of the methodology, explaining the theoretical background. The brewery (section 5.2) and dairy case studies (section 5.3) start with a brief description of the company background and present the results of a general company assessment. These two case studies provide a test bed for application of the methodology and represent two food industry company categories: small and medium-sized enterprises (SMEs) (section 5.2) and large enterprises (LEs) (section 5.3). Essential energy-related differences between these categories are addressed, with these case studies enabling direct comparison. The required methodological elements (section 4.4) are outlined in the procedure, but energy engineers from the manufacturing companies also participate in application of the methodology.

The focus of the case study discussion is on verifying and evaluating application of the methodology. As background, we therefore first present the results obtained using the identified tools and methods. The choice of the two company categories enables not only an evaluation of individual energy management within each, but also comparison. The two categories also reflect defined users (company energy engineers, section 4.5). User feedback is a key element of application-related verification of the methodology. Figure 5.1 illustrates the structure of this methodological evaluation.

Findings from	Application of tools, measures and methods	Company category	Energy manger feedback
Verification and evaluation	• General handling of use • Application effort • Contribution to company development	• Differences regarding energy behaviour • Handling of energy data	• General methodology application • Tools, measures and methods • Effect on expertise

Figure 5.1: Structure of methodological evaluation

This discussion concludes with a review of application of each element within the two case studies, and a related assessment of functions and tools. As Figure 5.2

shows, the assessment first identifies functions and related tools, also describing necessary conditions and challenges of application. It further describes the benefit to the company of using a particular tool. Also of importance is function assessment (last column). This describes, within a range from 0–100%, whether the function and its tools are covered by company expertise and therefore, whether or not these are essential for application of the methodology. If this is not essential, however, this does not mean that it can be omitted, because its inclusion remains necessary to ensure the completeness of the methodological. The last row finally provides the element average for all functions (equal value for each).

Function	Tools	Condition(s)	Challenge(s)	Case study company benefit	Tool assessment	Function assessment
Name	Name	---	---	• Brief description of benefit	0-100%	0-100%
				Element Average of function assessment	0-100%	

Figure 5.2: Assessment of function within case study company

5.1 Tools and methodological application

The case study application of the methodology considers each element independent. The flow chart in Figure 5.3 illustrates the procedure from 'Energetic Analysis' (I.) to 'Simulation' (IV.) with the interconnections of the elements as well as the parts of methodology designer and energy engineers:

On the one hand the flow chart (Figure 5.3) shows the main result of each element. For the element 'Energetic Optimisation' (II.) this is the (re)design of a low-grade heat system. Additional results of this element are for example the energetic benchmark or heat recovery potentials. The flow chart connects (black arrows) further results of one element to other elements. This means transfer of information and is necessary input for the application of the connected element. 'Solar Process Heat System' (III.) gets for example the (re)design of the low-grade heat system as input for the redesign of a low-grade heat system with solar process heat. Information is also transferred within one element. Heat recovery potentials are input for the (re)design of the low-grade heat system in element

'Energetic Optimisation' (II.). The final element 'Simulation' (IV.) transfers information back to previous elements. This enables for example an iterative optimisation of the low-grade heat system with solar process heat within the element 'Solar Process Heat System' (III.).

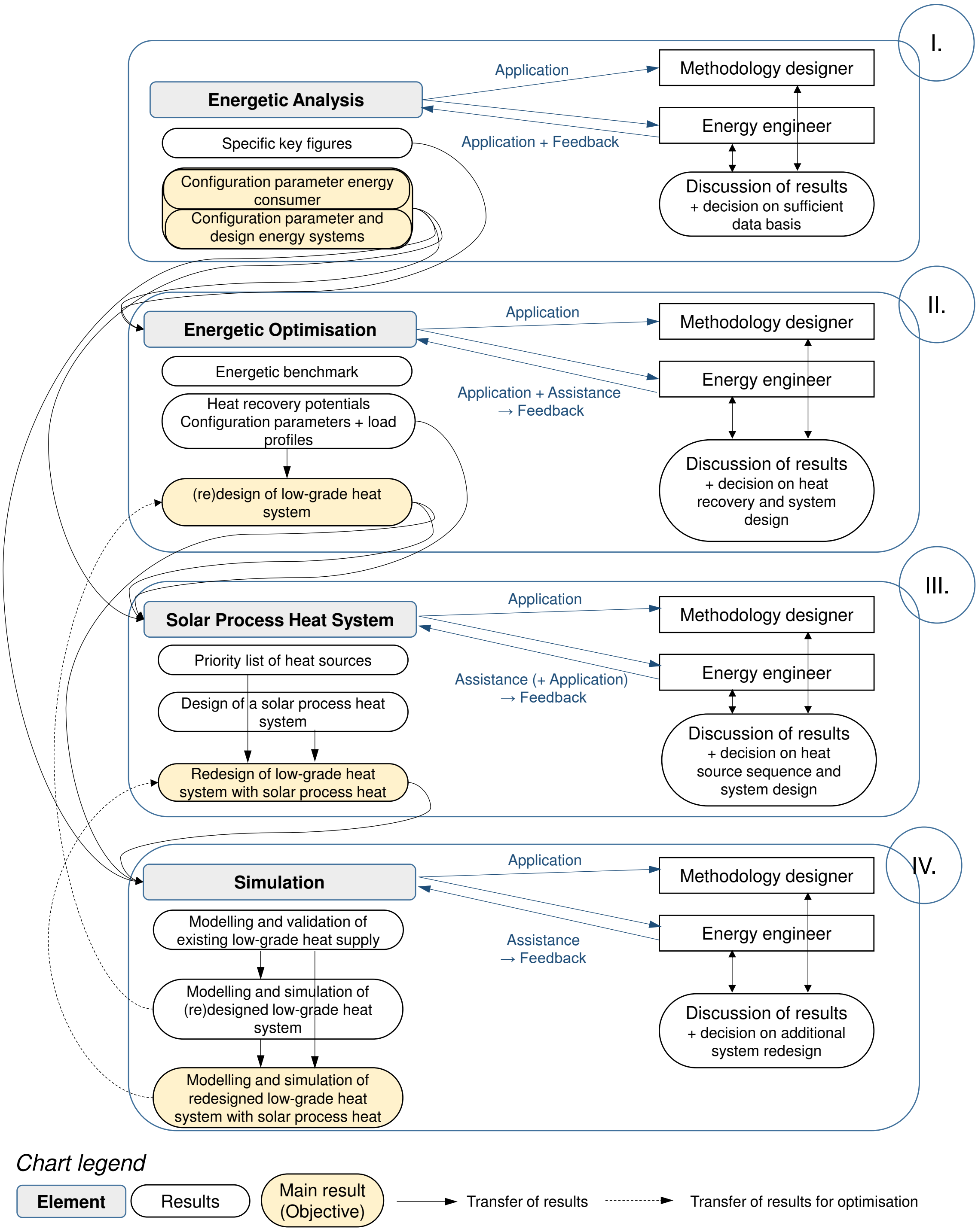

Figure 5.3: Application of methodology elements

On the other hand the flow chart (Figure 5.3) illustrates the cooperative methodology application by the methodology designer and the energy engineer as well as the feedback by the energy engineer. The cooperation includes the continuous discussion of the results of each element and the decision making on important aspects, e.g. that the data recorded within element 'Energetic Analysis' are sufficient to meet the objective and results.

5.1.1 Energetic analysis

The first element, energetic analysis, provides knowledge that is fundamental for the whole methodology. This includes total company energy demand, energy supply and distribution systems, as well as energy demand of specific processes and applications. This information provides inputs for optimisation, design of the SPH-system, and simulation, and its quality consequently significantly influences application of these elements. The scope and detail of relevant energy and process data are critical considerations. In an ideal situation, a permanently installed system would continuously record all relevant energy supply data and distribute these at both network and process levels.

The objective of this element is a complete and detailed illustration of the energetic behaviour of the manufacturing company.

5.1.1.1 Energy Balance

Energy balances relate to analysis of energy consumption and CO_2 emissions across the entire spectrum, from a company's site to its service areas (e.g. the heat distribution network), and need to be spatially defined. Definition of constant periods enables evaluation of energy consumption over several periods. In combination with production volume, energy balances form the basis for specific energy-based or ecologically based key figures. These enable comparison with other companies and are essential for benchmarking. The quality of energy balances is reliant on available data relating to company energy consumption or energy distribution systems for a defined period. Data acquisition is thus a critical factor.

Preparing an energy balance requires the following:

1. The first step is to define the *balance area* by setting boundaries around the system and identifying the form of energy to be analysed. Schieferdecker (2006) defines the basic forms of energy for a company energy balance, including final energy, energy losses, useful energy, and energy transmission (Eq. 5.1). Energy transmission refers to energy supply to other companies.

$$\Sigma Q_{Fin} = \Sigma Q_{los} + \Sigma Q_{Use} + \Sigma Q_{Trans} \qquad \text{(Eq. 5.1)}$$

   Figure 5.4 illustrates provides an example of a balance area. It shows the ingoing form of final energy and outgoing finished products. This can be applied to a production site or to a restricted energy distribution system. The most significant form of energy for production companies is final energy Q_{fin}, relating to process heat supply, cooling, or pressurised areas. Energy resources are also relevant for CO_2 emissions. Also of significance are useful energy (Q_{use}) and energy losses (Q_{los}). The main focus is on energy required for production. Energy transmission is not of interest in this case and is not considered.

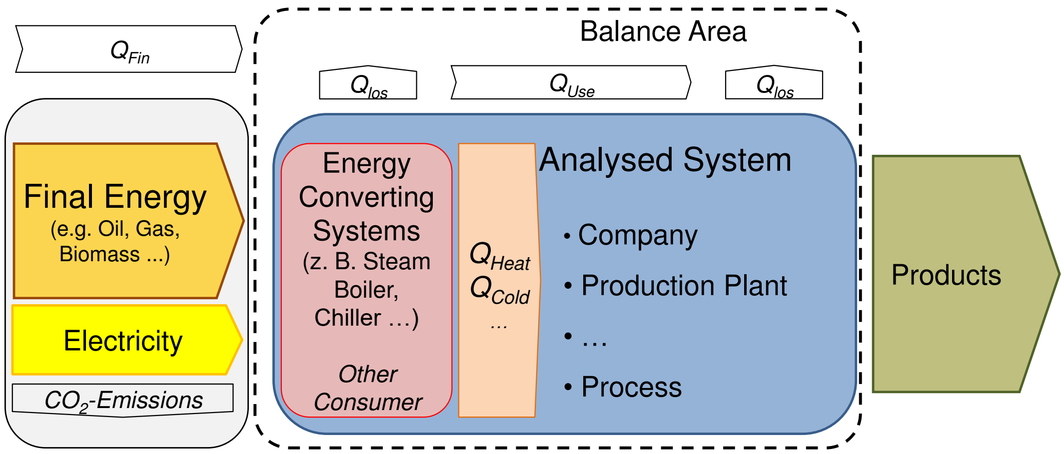

Figure 5.4: Definition of balance area

2. The second step is the definition of a *balance period* for continuous control of energy consumption. A period spanning January to December is advantageous for analysis of SPH-systems.

3. The third step is *collection* of necessary *data* for the energy balance. As shown in Figure 5.4, both energy and production data must be acquired.

4. The last step is *analysis* of collected data and definition of specific *key figures* for a benchmark. It is useful to distinguish between energetic and ecological figures. Table 5.1 shows examples of significant key figures, based on different reference values.

Table 5.1: Example definitions of specific key figures

Category	Meaning	Unit
Energetic	Thermal energy consumption per unit of processed raw material	$kWh_{th}\ PU_{RM}^{-1}$
Energetic	Electricity consumption per unit of finished product	$kWh_{el}\ PU_{FP}^{-1}$
Ecological	GHG-emissions per unit of processed raw material	$g_{CO2Equ}\ PU_{RM}^{-1}$

Greenhouse gas emissions from fuels are used to determine ecological key figures. These include emissions from combustion as well as from fuel production, and include the primary gases CO_2, CH_4, N_2O, and other halogen-containing compounds. The result is a CO_2-equivalent value using 100-year global warming potential (Solomon, 2012).

5.1.1.2 Energy supply and distribution

Energy supply and distribution systems form the energetic basis of industrial production. Thermal-driven processes dominate the food industry (section 2.2). From an energetic point of view, mechanical processing is of minor importance. The dominant energy source for process heat supply is the steam boiler, while systems with compression chillers supply cooling energy. Pressurised air is also necessary for various applications.

Fuel for heat generation is almost always either gas or oil; occasionally, biomass-fired steam generators are used. Electric energy is used to drive air compressors and compression chillers. Table 5.2 gives an overview of energy-providing systems.

Table 5.2: Common energy supply systems in the food industry

	Energy Source	Energy	Energy Medium
Steam boiler	Gas or oil	Thermal energy	Steam/High-pressure hot water
CHP-unit	Gas	Thermal energy	Hot water
Chiller	Electricity	Thermal energy	Cold water / Refrigerant
Air compressor	Electricity	Compressed air	Compressed air

As illustrated in Table 5.2, three categories of energy distribution networks are defined in the food industry, with reference to process heat, cooling, and compressed air. An energy network consists of the energy supply unit, the transfer medium for energy distribution, and the energy consumer.

A detailed analysis of energy distribution networks starts with an energy balance (comparable to that described in section 5.1.1.1). Relevant data are based on network documentation and configuration parameters (Figure 5.6) of energy supply units, on energy distribution, as well as on energy consumers.

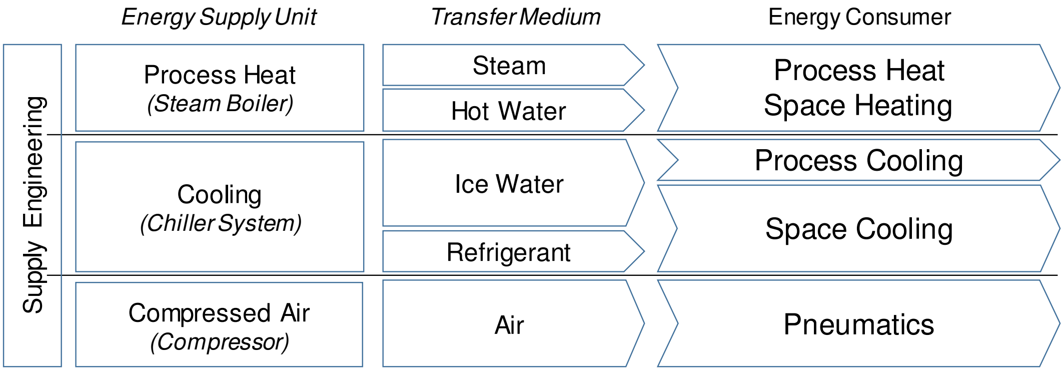

Figure 5.5: Energy network categories

Network load profiles complete the analysis. In addition to energetic facts, an analysis of energy distribution network components is required. This relates to the definition of equipment that can be used within a further reconfiguration, but also to integration with an SPH-system. In this case, heat storage is of particular interest.

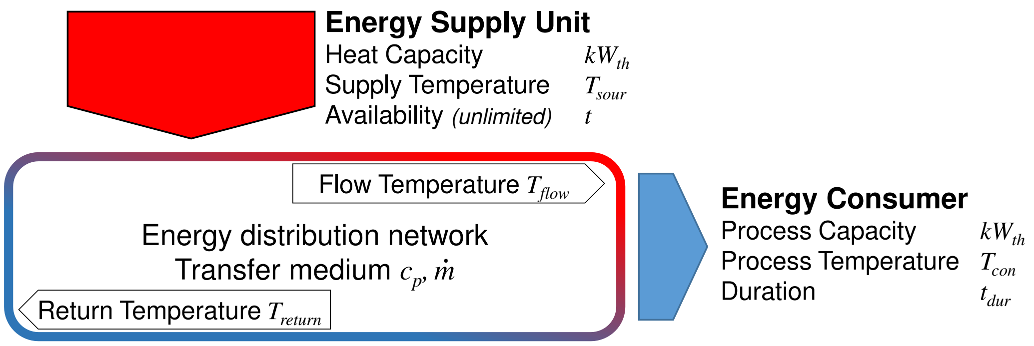

Figure 5.6: Network design and configuration parameter

The company production structures provide additional background for analysis of energy distribution to energy consumers. It is useful to simplify these structures and divide them into sections, in order to evaluate the energetic parameters of each. Figure 5.7 presents a graphical analysis of sections and their associated energy demand; as can be noted, a distinction is made between process heat-consuming ‘hot areas’ and cooling energy-consuming ‘cold areas’.

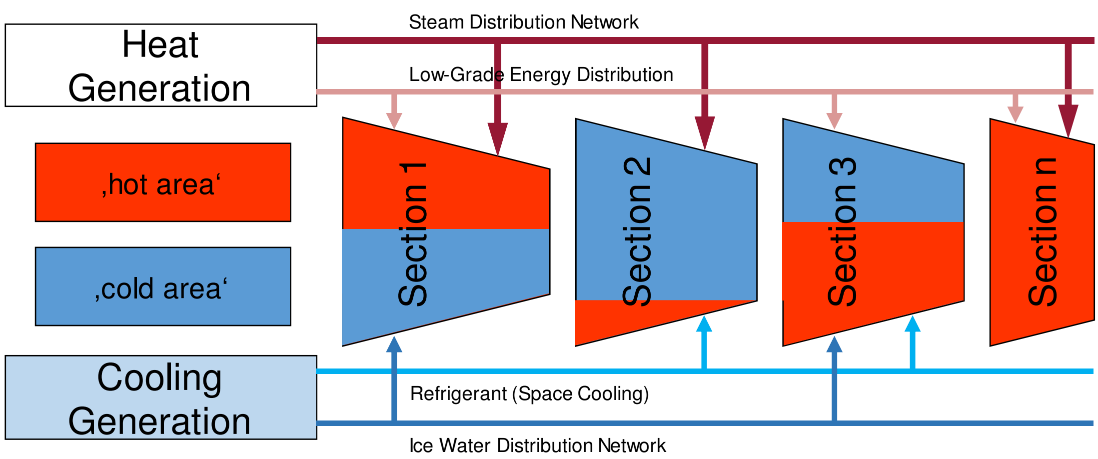

Figure 5.7: Production sections and energy supply

Energy supply to a section depends on supply capacity and energy demand, but also on process temperatures. Maximum and minimum temperatures of each section need to be identified to configure an optimised energy supply. These also serve as inputs for analysis of heat supply from waste heat sources or for integration of the SPH-system. The analysis follows the scheme shown in Table 5.3.

Table 5.3: Process temperature section 1

	Min. temperature	Max. temperature
Process Heat	35 °C	140 °C
Cooling	7 °C	18 °C

5.1.1.3 Energy consumers

Energy consumers are represented by production processes and other energy-consuming applications (e.g., cleaning or space heating) with similar specifications (Table 5.4). Analysis is dependent on the availability of detailed data. Heat capacity and target temperature T_{tar} are defined as maximum values for consumptive operation. Process heat demand for a consumer run (batch) depends on duration.

Table 5.4: Specification of processes and applications

	Heat Capacity	Process Heat	Duration	T_{tar}
Process	kW_{th}	kWh_{th} bat^{-1}	min.	°C
Application	kW_{th}	kWh_{th} bat^{-1}	min.	°C

Continuous energy consumption can be analysed based on process description specifications. Discontinuous energy consumption requires additional time-related data. In contrast to energy balance data available from company energy accounts (Table 5.5), such process data is also required for specific systems. It is therefore advantageous to have a manufacturing execution system (MES) that continually acquires data, providing load profiles and consumer specifications for analysis.

Table 5.5: Levels of analysis and data acquisition

Level	Data	Source	Availability and Effort
Company	Energy [kWh_{el}]	Account	simple
Production process	Power [kW] Temperature [°C] Time [s]	EMS, Temporary Measurement	more complex, comprehensive

Temporary data acquisition can compensate for missing MES data. Energy consumer information provides background knowledge for subsequent energetic optimisation, and should incorporate all consumers.

Inclusion of the production method in energy consumer analysis allows for consideration of its influence on the load profile of energy supply. A general distinction is drawn between continuous and discontinuous production, resulting in constant or fluctuating energy demand. Manufacturing in the food industry is mainly discontinuous, with batch production. The same equipment is often used for several products with different energy demands. A further effect of batch processing is time dependency of heat capacity. As shown in Figure 5.8 for the example of a multi-phase process, heat capacity drops from 5.5 kW hl^{-1} during heating to 3.9 kW hl^{-1} during boiling phase 1. It then falls to zero during rest, before returning to 3.7 kW hl^{-1} during boiling phase 2. After the 95-min wort boiling process, equipment is discharged and there is no further demand for energy until the next batch cooking process. The batch process therefore requires fluctuating energy supply (process heat as well as cooling). Such behaviour is not only the case for production processes but also for applications such as cleaning of production facilities with CIP.

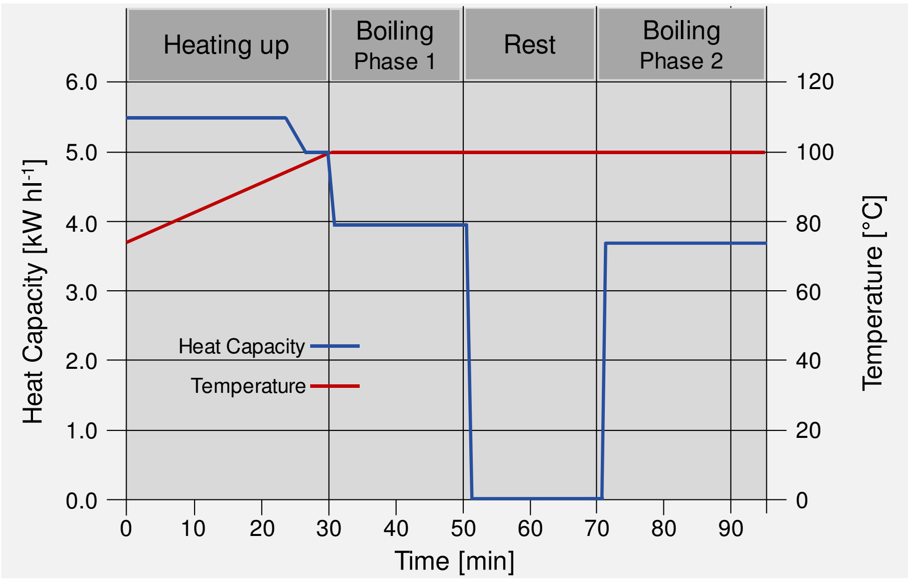

Figure 5.8: Characteristics of a boiling process (cf. Steinecker, 2012)

Actual energy demand of a production section or complete production site is determined on the basis of combined data for several energy consumers. Integrating the production plan with analysis of energy consumers can be useful to identify energy peaks when there are several energy consumers in parallel.

5.1.2 Energetic optimisation

The energetic optimisation aims to develop heat distribution concepts for integration of SPH-systems. This analysis provides background information. Optimisation potential is determined from analysis of energy consumers (processes) and existing system configuration for low-grade heat supply. Pinch analysis, as an optimisation tool, determines heat recovery potential.

The objective of this element is low-grade heat distribution that combines suitable energy consumers with heat recovery and conventional energy supply.

5.1.2.1 Optimisation potential

Based on analysis of low-grade process heat consumers (heat sinks) and low-grade heat sources, energetic optimisation aims to achieve an energy-efficient combination of both. Heat sources and sinks are classified on the basis of:

- temperature T,
- heat capacity kW_{th},
- heat energy kWh_{th},
- availability or duration t.

Figure 5.9 illustrates the matching of heat sinks and heat sources that forms the basis of energetic configuration of a heat supply. Energetic combinations can vary from direct process heat supply from a single source or specific sink, to a full low-grade heat distribution network. The configuration of various heat sinks and heat sources to low-grade heat distribution is the focus of optimisation, within the goal of SPH-system integration. The main objective to minimise fossil energy use is identification of useful heat sources, i.e., waste heat from chiller systems, air compressors, or processes.

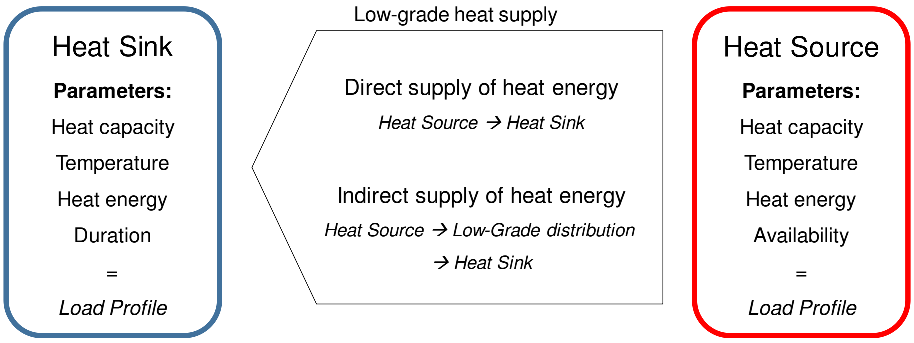

Figure 5.9: Parameter comparison of heat sinks and heat sources

Pinch analysis (Bodo Linnhoff) is a tool for optimising energy demand (Kemp, 2007). The method defines minimal cooling supply and minimal process heat supply. All processes with cooling energy demand are therefore added, as are all processes with heat energy demand. A heat exchanger network combines these hot and cold processes and enables direct exchange of energy. The configuration considers different temperature levels of the processes but also heat capacity demand, and results in minimal cooling and heating requirements. This can be illustrated with a composite curve (Figure 5.10).

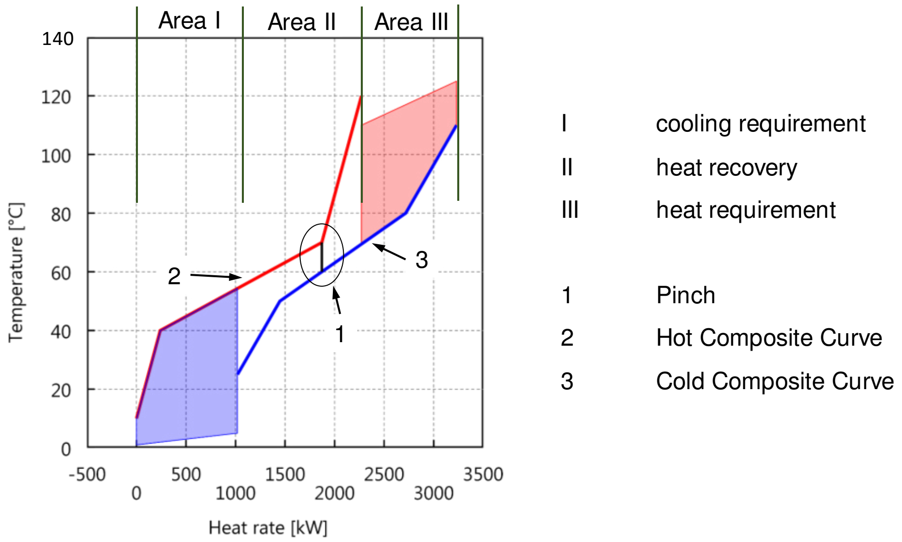

Figure 5.10: Example of composite curve

A disadvantage of pinch analysis is its use for continuous processes. Batch processes dominate in breweries and dairies and use of pinch analysis thus requires some modification. Krummenacher (2002) modified the approach and developed new pinch analysis methods to handle batch processes and the various related challenges. An essential approach is integration of time dependency of batch processes. Figure 5.11 describes the problem of heat exchange between processes that do not run in parallel. Cold batch 1 is running from t_{start} = 0 to t_{stop} = 0.3 with a constant heat rate of 20 kW_{th} heating requirement and hot batch 1 is running from t_{start} = 0.4 h to t_{stop} = 0.8 h with a constant heat rate of 30 kW_{th} cooling requirement. The same applies for batch 2 that starts at t_{start} 1.0 h. Direct energy exchange is not possible with this configuration. The approach involves indirect heat exchange with integration of heat storage. As illustrated in Figure 5.12, heat energy of hot batch 1 is pre-stored and made available for later application.

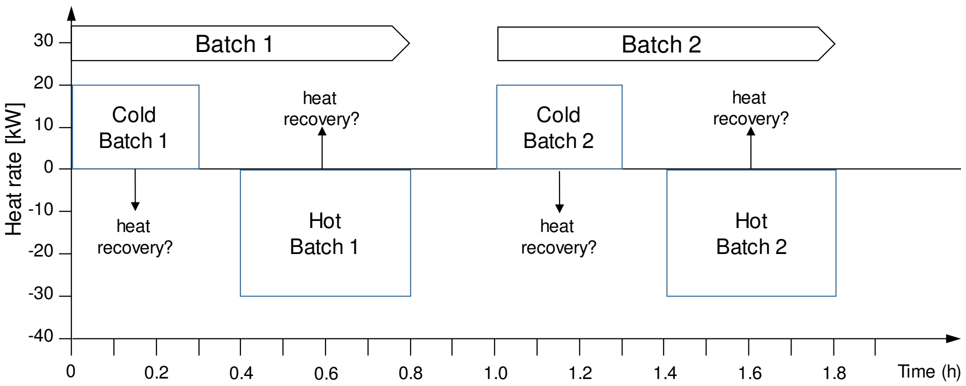

Figure 5.11: Example of batch processing

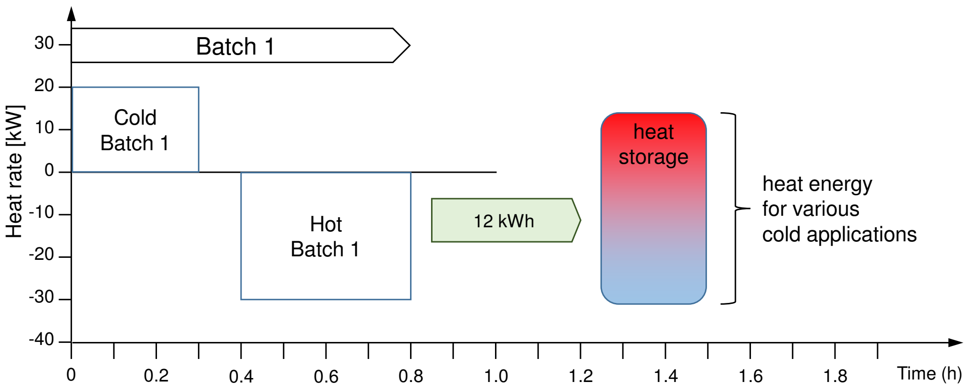

Figure 5.12: Batch processes with heat storage integration

Heat storage provides the possibility of having indirect process heat recovery with batch processes. However, in comparison to direct heat exchange, storage causes additional energy losses. Losses must be considered and included in the energy balance of the system. Figure 5.13 shows a heat recovery circuit (*HRC*) with heat recovery from hot batches, heat supply to cold batches, and heat storage with energy losses.

- Q_{hb} heat recovery from hot batch to heat storage
- Q_{cb} energy supply to cold batch from heat storage
- Q_{loss} energy losses from heat storage

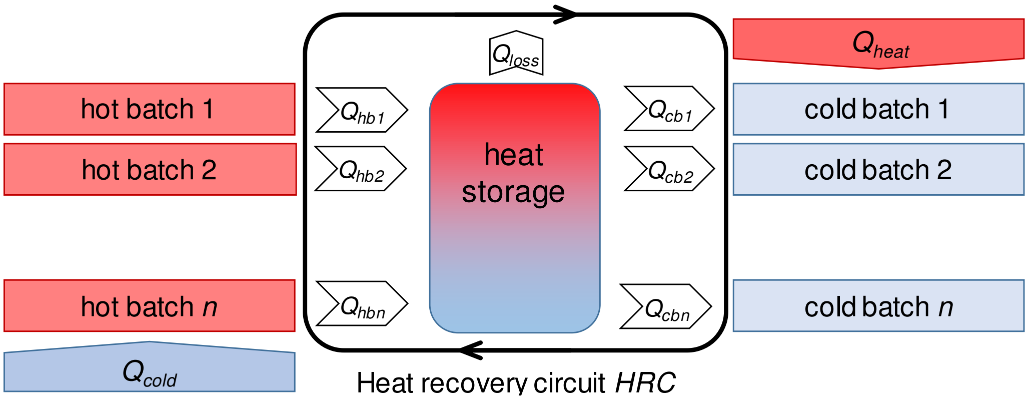

Figure 5.13: Heat Recovery Circuit *HRC*

This HRC provides the basis for an energy balance to define energy losses of heat storage as well their significance for total heat recovery. (Eq. 5.2) defines the heat recovery potential HR_{pot}:

$$HR_{pot} = \sum Q_{hb} - \sum Q_{cb} - Q_{loss} \qquad \text{(Eq. 5.2)}$$

Temporary storage does not only cause energy losses but also requires additional equipment. A second approach is therefore needed to enable direct heat recovery with batch processes, via rescheduling of the production flow. However, technical and energetic aspects are limited by the following (cf. Kemp, 2007):

- Individual duration and different heat rates lead to different loads;
- The process occurs in a vessel and does not flow through a heat exchanger;
- The same equipment is used for heating and cooling.

Figure 5.14 illustrates rescheduling for batch 2 of the example given. Hot batch 2 now starts at the same time as cold batch 2. Direct heat recovery is possible but is limited to 6 kWh_{th} because of different loads. For this reason, 6 kWh_{th} of external cooling are always necessary. Rescheduling stands for a change of production. This requires not only its technical feasibility (e.g. not possible in case of multiple equipment use) but also the readiness of the company. A combination of both indirect heat exchange and rescheduling provide a promising option.

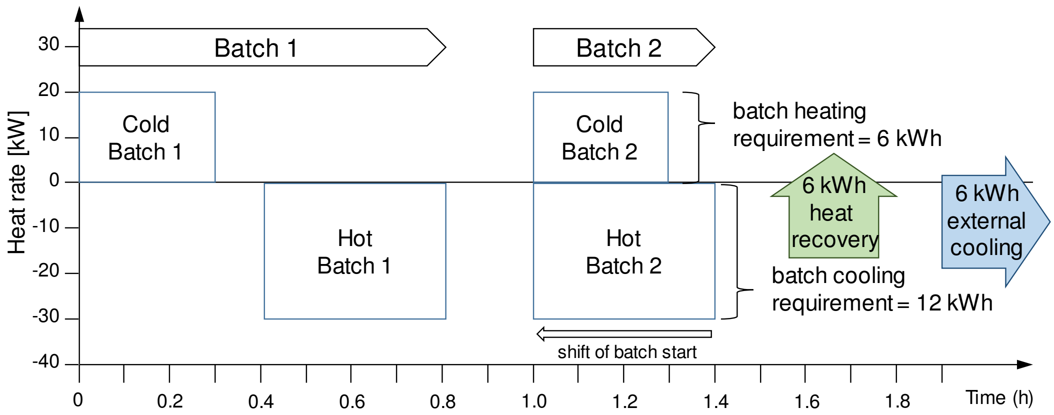

Figure 5.14: Rescheduled batch processing

5.1.2.2 Heat recovery

Waste heat contributes significant fractions of the energy demand in low-grade heat distribution concepts and therefore substitutes for external energy. The analysis distinguishes between two categories:

- Waste heat from production processes; and
- Waste heat from non-energy generators.

<u>Heat recovery from production processes</u> is a broad field of application. Many processes in the food industry require cooling and therefore provide waste heat. The waste heat sources in breweries and dairies are mainly hot intermediate and finished products on the one hand, and vapors of production processes on the other. It is technically feasible to recover large amounts of such waste heat. In order for use to be practical and efficient, the energy consumer would require:

- sufficient high source temperature (preferably higher than the supply temperature of the energy consumer),
- sufficient high heat capacity of the waste heat source, and
- long constant operation time (availability).

As described with reference to pinch analysis (section 5.1.2.1), batch processes complicate process heat recovery. Table 5.6 compares the characteristics of batch and continuous processes. Process load profiles provide additional information regarding process mass flows or temperature variations.

Table 5.6: Characteristics of process evaluation for heat recovery

Process category	continuous	↔	batch
	'flowing' process *(product in a pipe)*	↔	'stationary' process *(product in a vessel)*
Energy supply	heat energy	↔	cooling energy
Heating capacity	constant	↔	intermittent
Energetic specification	mass flow [kg s^{-1}]	↔	mass [kg]
	specific heat capacity [kJ kg^{-1} K^{-1}]		
	initial temperature T_{in}	→	target temperature T_{out}
Process interval	start time t_{start}	→	stop time t_{stop}
Equipment layout	spatial division		

<u>Heat recovery from non-heat generators</u> refers to heat recovery from cooling systems and air compressors. Both are promising low-grade heat sources. These systems are common production and storage components in breweries and dairies. Electric energy drives chillers and air compressors. Due to system technology, some propulsion energy is lost as waste heat and can be recovered.

Cooling systems in breweries and dairies are mainly compression refrigerant systems and work with ammonia as a refrigerant. Heat recovery is possible from deheating of hot gas and subsequent condensation of refrigerant (Reindl and Todd, 2007).

Hot gas deheating reflects just 10–15% of total heat recovery potential. Depending on operational conditions, it can provide favourable waste heat temperatures of up to 90 °C. The remaining heat recovery potential is met by condensation. However, the useful temperature of this is 20–35 °C lower and therefore of only limited usability. Figure 5.15 presents the configuration scheme of a cooling system, illustrating heat recovery from condensation and hot gas deheating from the refrigerant circuit.

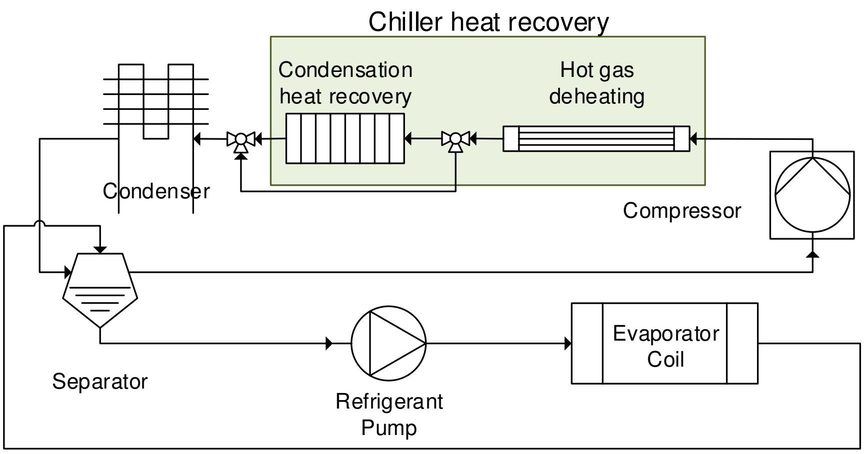

Figure 5.15: Scheme for cooling systems with heat recovery

Heat recovery from air compressor systems occurs from the cooling circuit. Promising heat sources here including the water cooling/oil lubricant circuits (Figure 5.16). This can reach temperatures of up to 75 °C. Simple integration with plate heat exchangers for various energy consumers is possible. The temperature from air-cooled systems is much lower and usability is limited. Such systems provide energy for space heating using air duct technology (Bierbaum, 2004).

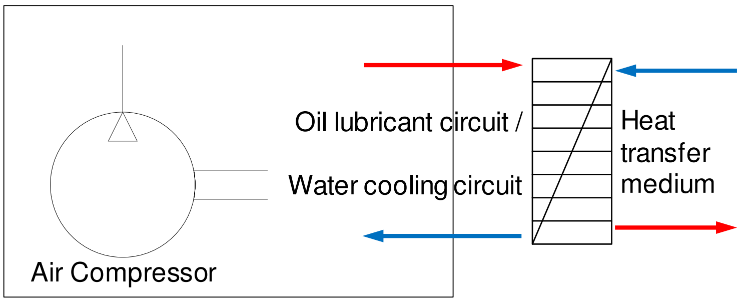

Figure 5.16: Heat recovery from air compressor with liquid cooling

Non-heat generators can supply large amounts of waste heat. As described earlier, a sufficient source temperature is essential for usability. This varies, depending on specific system configuration, between 20–90 °C (Table 5.7).

Table 5.7: Example temperature levels of waste heat

	System energy source	Temperature
Chiller	Hot gas deheating*	30–90 °C
	Refrigerant evaporation*	20–35 °C
Air Compressor	Cooling circuit	30–75 °C

* Depending on chiller configuration; refrigerant ammonia

Technical availability and energetic potential are important background considerations for efficient integration of waste heat within energy distribution systems. The calculation of heat recovery potential is based on parameters of the source medium (Table 5.8). These are comparable for processes, cooling systems, and air compressors.

Table 5.8: Parameter for heat recovery potential

		Process	Cooling system	Air compressor
Source temperature	T_{sour}			
Target temperature	T_{tar}		refrigerant	cooling liquid
Mass flow	$\dot{m}$	process medium		
Thermal capacity	c_p			
Duration	t_{dur}		---	---
Availability	t		refrigerant	cooling liquid

The source temperature, in combination with target temperature, mass flow, and thermal capacity of the source medium result in heat capacity $\dot{Q}_{hr,th}$ (Eq. 5.3) of the waste heat source.

$$\dot{q} = \dot{m} \times c_p \times (t_{sour} - t_{tar}) \qquad \text{(Eq. 5.3)}$$

Heat exchanger technology and the method of heat supply determine actual energy use of energy consumers. Additionally, source availability and duration of energy consumption determine total energy use from waste heat.

5.1.2.3 Concept development

Concept development is aimed at configuring a low-grade heat supply, based on the background analysis of energy supply and distribution of existing structures (section 5.1.1.2). An essential aspect for concept development and energetic configuration is network flow temperature, which needs to be able to supply connected energy consumers. A low return temperature is equally important, ensuring maximum heat recovery and promising conditions for SPH-systems.

The focus is on an integration of all available waste heat sources to the distribution network. This means that an efficient combination of heat recovery and conventional energy supply is necessary for backup (Figure 5.17). Heat supply to the network (from all sources) supplies the full energy demand of energy consumers. The integration of heat storage can compensate for differences between availability of waste heat and duration of energy consumption (section 5.1.2.1).

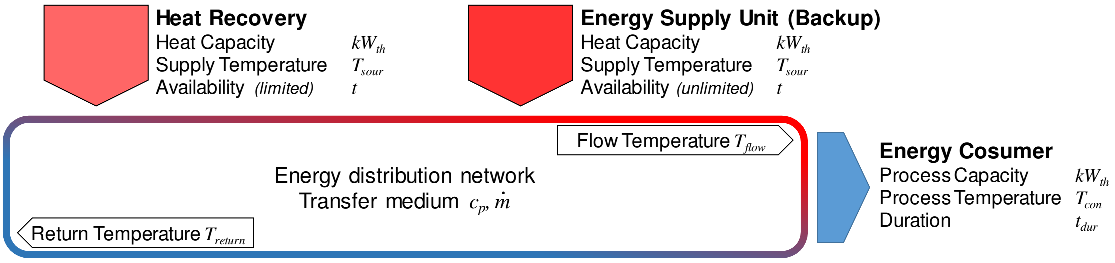

Figure 5.17: Network design with heat recovery

A useful tool for configuration of the concept is, again, energy balance. This compares energy demand of the consumer $Q_{th,con}$ and energy supply from heat recovery $Q_{th,hr}$, to define the necessary heat supply from backup $Q_{th,backup}$. As equation (Eq. 5.4) illustrates, the balance also considers distribution losses $Q_{th,loss}$.

$$(Q_{th,con} + Q_{th,loss}) - Q_{th,hr} = Q_{th,backup} \quad \text{(Eq. 5.4)}$$

The equation is modified for definition of maximum network heat capacity (Eq. 5.5). It assumes simultaneous availability of sources and duration of energy consumption or analysis at a certain point in time. Time-related analysis based on fluctuating heat capacities requires load profiles:

$$(\dot{Q}_{th,con} + \dot{Q}_{th,loss}) - \dot{Q}_{th,hr} = \dot{Q}_{th,backup} \quad \text{(Eq. 5.5)}$$

The energy supply from backup $Q_{th,backup}$ gives a first parameter for configuration of the SPH-system.

5.1.3 Solar process heat system

Solar process heat is able to substitute conventional with renewable energy. The focus is, first, on energy-efficient system (section 5.1.2.3) configuration. This configuration needs to be feasible for implementation at company buildings and for integration with a low-grade heat supply. Second, SPH-system configuration aims at economic efficiency, with the following requirements:

- use of cost-effective flat plate collectors;
- use of market-available system components;
- simple system configuration;
- integration of existing structures at the company; and
- system design for economically efficient operation and maintenance.

The focus of system design is a maximum value of specific collector earnings $kWh_{th}\ m^{-2}{}_{ca}$.

The objective of this element is SPH-system design and its integration with the developed low-grade heat supply concept for energetic optimisation.

5.1.3.1 Application potential

SPH-systems supply (with the exception of electricity for pumps and control) fuel-free and almost CO_2-free process heat. Depending on system configuration and energy consumers, specific collector earnings can reach > 800 $kWh_{th}\ m^{-2}{}_{ca}$ in southern European locations and about 500 $kWh_{th}\ m^{-2}{}_{ca}$ in central European locations (SHC, 2012; Mayer, 2007). In addition to configuration, location therefore has a large influence on SPH-system energy production.

A key measure for SPH-system evaluation is annual useful energy from storage $Q_{use,stor}$, as this represents useful energy for substituting fossil fuels. The overall efficiency of the solar system SOL_{eff} is the ratio of $Q_{use,stor}$ to energy from the collector array Q_{col} (Eq. 5.6).

$$SOL_{eff} = \frac{Q_{use,stor}}{Q_{col}} \quad \text{(Eq. 5.6)}$$

Figure 5.18 illustrates the evaluation scheme, with an example of an SPH-system divided into three balance areas. This supports detailed analysis for identifying sensitive areas and assigning heat energy losses.

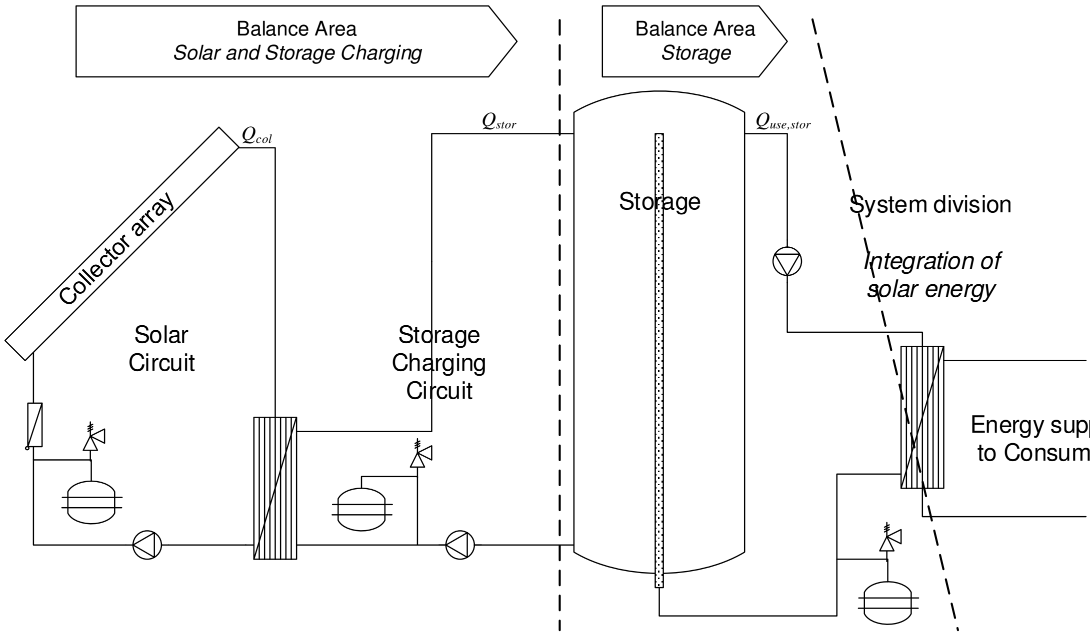

Figure 5.18: Balance area for a dual circuit SPH-system

Balance Area *Solar and Storage Charging*

The balance area *solar and storage charging* includes a collector array, a solar circuit, as well as a storage charging circuit. The energy output of this balance area is the energy supplied to storage Q_{stor} (Eq. 5.7). Energy supplied to storage depends on the energy from collector array Q_{col}, energy losses from piping $Q_{loss,pip}$, and transmission efficiency η_{he}.

$$Q_{stor} = (Q_{col} - Q_{loss,pip}) \times \eta_{he} \quad \text{(Eq. 5.7)}$$

Balance Area *Storage*

The balance area *storage* evaluates useful energy from storage. This is a result of storage efficiency and is affected by operational conditions and the quality of storage insulation. Storage heat loss $Q_{loss,stor}$ and energy supply to storage Q_{stor}, combined with transmission efficiency η_{he}, give the energy output $Q_{use,stor}$ (Eq. 5.8).

$$Q_{use,stor} = (Q_{stor} - Q_{loss,stor}) \times \eta_{he} \qquad \text{(Eq. 5.8)}$$

Solar Energy Potential

The solar energy potential $Q_{use,con}$ in (Eq. 5.9) represents the remaining energy demand of consumers $Q_{pro,con}$ after heat recovery Q_{hr}.

$$Q_{use,con} = Q_{proc,con} - Q_{hr} \qquad \text{(Eq. 5.9)}$$

Solar Fraction

The solar fraction f_{sol} (Eq. 5.10) is the proportion of solar energy supply from storage $Q_{use,stor}$ divided by solar energy potential $Q_{use,con}$.

$$f_{sol} = \frac{Q_{use,stor}}{Q_{use,con}} \qquad \text{(Eq. 5.10)}$$

Storage Utilisation Factor

The storage utilisation factor uf_{stor} is defined for evaluation of storage efficiency. It describes the ratio of useful energy from storage $Q_{use,stor}$ to energy loss from storage $Q_{loss,stor}$ (Eq. 5.11).

$$uf_{stor} = \frac{Q_{use,stor}}{Q_{loss,stor}} \qquad \text{(Eq. 5.11)}$$

5.1.3.2 System configuration

The main components of an SPH-system are collection and storage. Also of significance are system hydraulics, with pipe connections between collector arrays, storage, and energy consumers. The control strategy completes the system.

Figure 5.19 summarises system component and configuration aspects with a design matrix for the SPH-system. The objective defines the focus of each component and aspect. The aim of the collector system component is low investment, achieved by using a standard (commercial) flat-plate-collector. Storage volume is defined with a short-term objective, i.e., a storage period ranging from a few hours up to two days, and thus a specific storage volume of 50–80 l m_{ca}^{-2}.

System component Configuration aspect	Objective	Approach
Collector design	low investment	*flat-plate-collector*
Storage volume	short-term	*50-80 l m_{ca}^{-2}*
Storage charging	maximum useful temperature	*pipe connection* *stratified charging*
System hydraulic	operation safety	*serial collector strings* *parallel connected strings*
Flow management	maximum temperature difference	*low flow*
Heat transfer medium	frost protection	*water-glycol-mixture*
Control strategy	*maximum useful energy*	

Figure 5.19: SPH-system design matrix

Figure 5.20 illustrates the resulting SPH-system configuration. In a collector circuit, a heat exchanger separates the solar and storage circuits. The heat transfer medium in the collector circuit is a water-glycol-mixture and is responsible for frost protection. The heat transfer medium in the storage circuit is water; as this is located indoors, frost protection is not required. Storage in this figure is illustrated with a stratified charging system. Another defined charging variation is a pipe connection. The control is similar to the direct system. The collector pump starts with defined hysteresis ($T_{col} > T_{st,low}$). Bypass in this system is via the heat exchanger between the collector and the storage charging circuit. The storage pump also starts with defined hysteresis ($T_{byp} > T_{st,low}$). All connections are to the lower part of storage, as a result of stratified charging. This kind of configuration is very promising for integration with industrial low-grade heat distribution:

- It ensures time-related independence of solar process heat supply and energy consumption.
- Stratified charging optimises use of storage capacity and maximises available temperature from storage.
- The heat transfer medium (water-glycol-mixture) is frostproof and enables application at all locations in Europe.

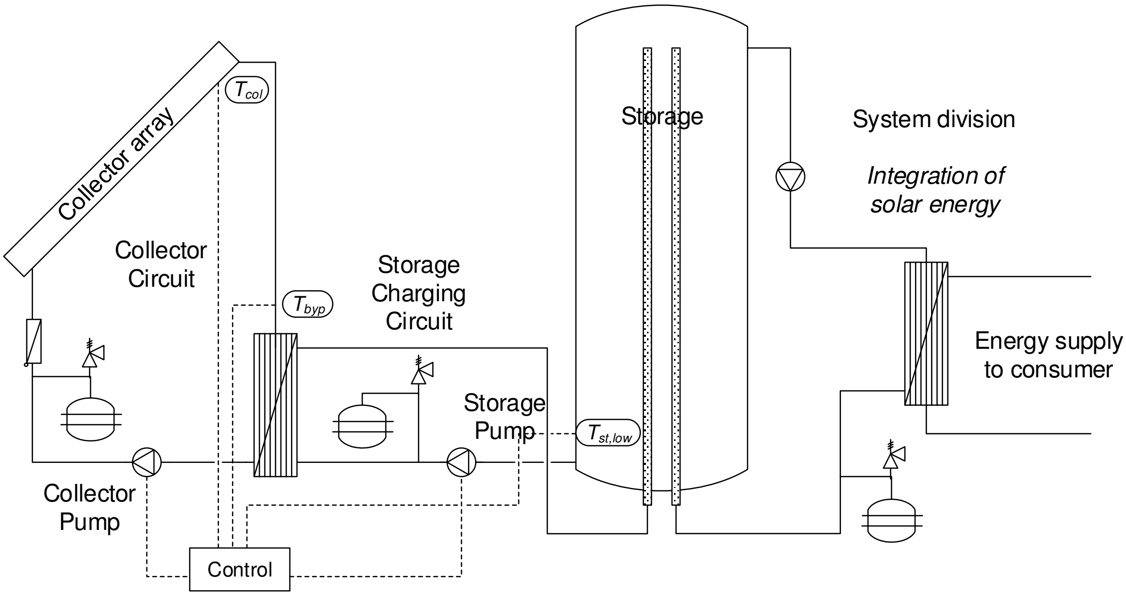

Figure 5.20: Solar Process Heat System with Stratified Charging Storage

Apart from system design, structural conditions must also be analysed. These includes, not only the area for collector mounting on buildings, but also storage locations, as well as the spatial distance between collector array, storage, and integration to consumers.

A large SPH-system needs large areas for mounting collectors. As Müller (2013) noted, an important restricting factor in the food industry is available area. The most promising areas for collector mounting are the roofs of company buildings. However, large roof areas do not necessarily equate to enough space for collectors. For a determination of useful collector area, Müller (2013) developed a methodology with an evaluation matrix, the initial point of which is the base area of the building. Roof design and roof orientation are evaluated with the *Collector Area Factor CAF* (Table 5.9). The *CAF* for a flat roof with south orientation, for example, is 0.5, and means that half the base is equal to the collector area.

Table 5.9: Examples of factors for roof evaluation*

	Direction	Collector Area Factor *CAF*	Comment
Flat Roof	South	0.5	Full area usable
Saddleback Roof	East to West	0.55	Only one roof side useable
Saddleback Roof	North to South	1.1	Both roof sides usable

*with regard to the roof ridge

*(Müller, 2013)

An example of the *Collector Area Factor CAF* (0.5) is given for a flat roof with south orientation, and for a saddleback roof with south orientation (1.1) (Figure 5.21).

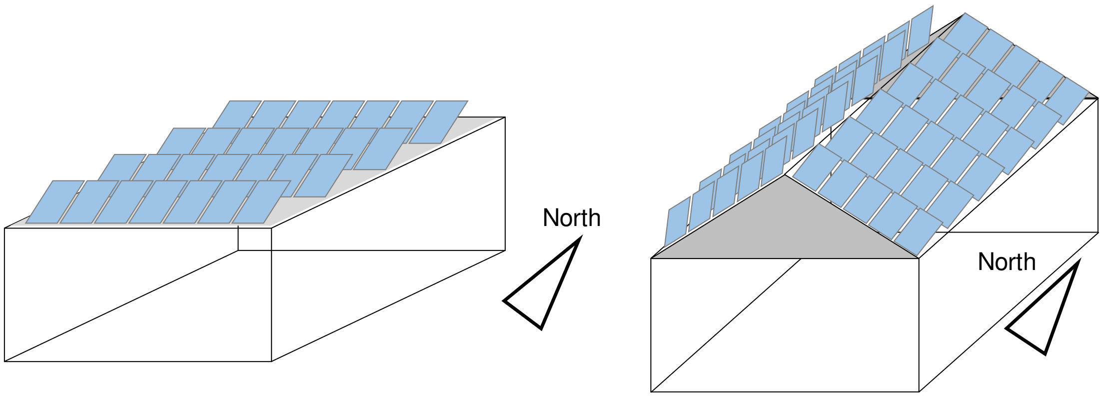

Figure 5.21: Exemplary collector mounting on flat roof (left picture) and saddleback roof (right picture) (Müller, 2013)

(Eq. 5.12) defines the resulting *Roof Area Factors B*, defining the maximum collector area.

$$B = BaseArea \times CAF \qquad \text{(Eq. 5.12)}$$

The core of the methodology is evaluation of roof structure on the basis of four criteria, taking into account area-reducing effects with the help of construction plans and aerial views of buildings:

- *Effectively available roof area*
  Areas with light domes, cooling towers, ventilation devices or any other structures must be subtracted from the total roof area.
- *Shading*
  This considers areas shaded by trees, chimneys, and storage tanks, reducing the effectively useable collector area.
- *Continuous areas*
  Continuous areas enable large contiguous collector areas with the advantage of optimal use of space.
- *Number of buildings*
  A large number of buildings results in numerous small collector arrays.

Table 5.10 shows criteria with their respective evaluation ranges. This range is for graduated building conditions.

Table 5.10: Evaluation criteria for roof structures*

Criteria		Evaluation Range (step rate)	Comment
C	Effectively available roof area	1 … 0 (0.1)	1 = all available
D	Shading	5 … 1 (1)	5 = no shading
E	Continuous area	5 … 1 (1)	5 = single huge area
F	Number of buildings	5 … 1 (1)	5 = single large building

*(Müller, 2013)

The result of the evaluation is the *Roof Structure Factor* I, within a range of 0.01–1.0. (Eq. 5.13) illustrates integration of the four criteria:

$$I = C \times \frac{(D + E + F)}{15} \qquad \text{(Eq. 5.13)}$$

The multiplication of *Roof Area Factor B* and *Roof Structure Factor I* gives the *Usage Factor II* (Eq. 5.14):

$$II = B \times I \qquad \text{(Eq. 5.14)}$$

Multiplying the *Usage Factor II* with the base area of the analysed building finally gives the useful collector area. However, it is not possible to evaluate the static conditions of roofs with this methodology.

Within the food industry, it is common to have a central boiler room for all energy supply equipment, and this serves as a starting point for the energy distribution network. It is hence appropriate for integration of solar process heat. Two questions must be answered in this regard:

- Is there heat storage available for solar energy, or enough space for heat storage?
- What is the distance between the boiler room and the collector array?

Regarding heat storage, the best option is an existing one with sufficient available volume for solar-energy integration. The second option is implementation of new storage. Large storage requires enough space and a high room, which is often not available, and storage can hence also be located outside the building.

5.1.3.3 Heat source management

The integration of solar process heat with a low-grade energy distribution network (Figure 5.17) is a main objective of the methodology. As Figure 5.22 illustrates, several waste heat sources with different properties (section 5.1.2.2) and solar process heat result in many combination possibilities. The major task is to find combinations that enable maximum energy use from heat recovery and an SPH-system, complemented with minimum backup energy. The backup energy supply should just cover gaps in heat capacity and ensure defined flow temperature.

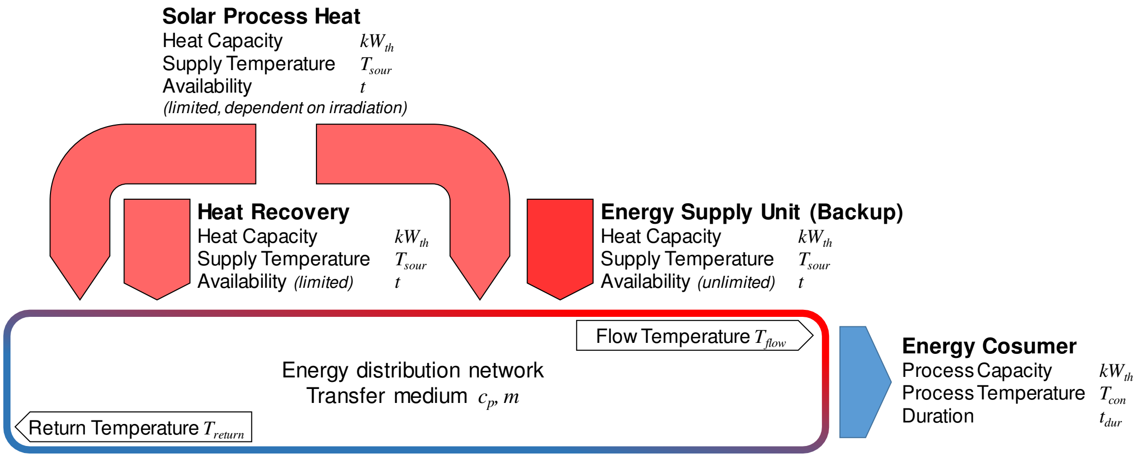

Figure 5.22: Network design with heat recovery and SPH-system

From an energetic point of view, the recovery of waste heat takes priority before implementation of additional – also renewable – heat supply systems. Many low-temperature energy sources, e.g., waste heat and SPH-systems, provide similar heat supply conditions. This can result in ‘competition’ between them and requires comparative evaluation of all source characteristics on the basis of energetic, technical, and economic parameters. Figure 5.23 illustrates a method that uses three levels of parameters for evaluation of each available heat source.

The first level is an evaluation of energetic parameters. Source temperature and heat capacity are the deciding factors. Many energy sources fluctuate, requiring further evaluation of availability. The energy supply from an SPH-system, for example, depends on solar radiation. Availability of heat sources first needs to be adequate to cover consumption duration. Energetic evaluation is supported by a list of criteria, including source temperature, heat capacity, and simultaneousness of availability and demand. The energetic value of a heat source increases with constants in heat capacity, source temperature, and availability. At a second level of implementation, technical parameters are used to evaluate the implementation of a heat source in relation to consumers, necessary equipment, and reconstruction efforts involved. Energetic and technical evaluations provide final input for economic evaluation, at a third level. The evaluation results in a priority list of evaluated heat sources.

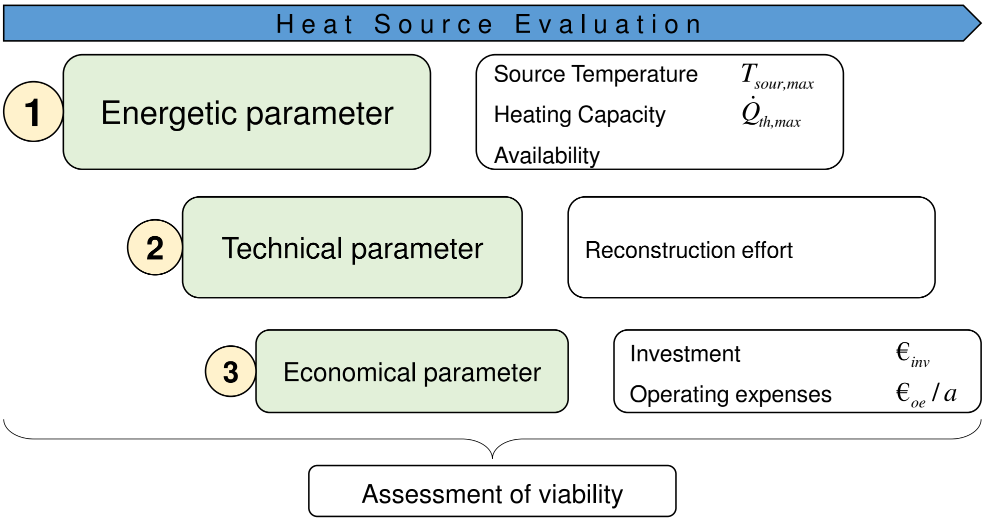

Figure 5.23: Parameter for heat source evaluation

Figure 5.24 presents a comparison of different heat sources and explains matching with consumers based on defined criteria, illustrating the energetic evaluation described above. The figure shows process heat supply to the consumer but also the possibility of cooling energy supply from consumer to heat sources.

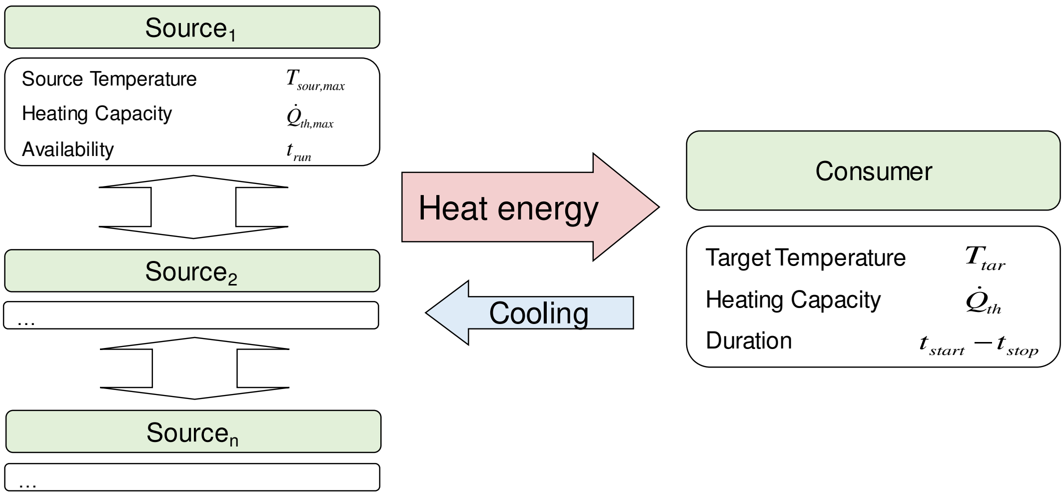

Figure 5.24: Heat source evaluation matching with energy demands of consumer

The evaluation of heat sources finally provides the necessary information to develop a heat source sequence, enabling energy-efficient concept development. However, this is not a final solution; in reality, this is the starting point for continuous improvement of heat distribution between heat sources and energy consumers. Manufacturing companies must be flexible with regard to new heat sources and energy consumers. The optimisation circuit in Figure 5.25 illustrates this process.

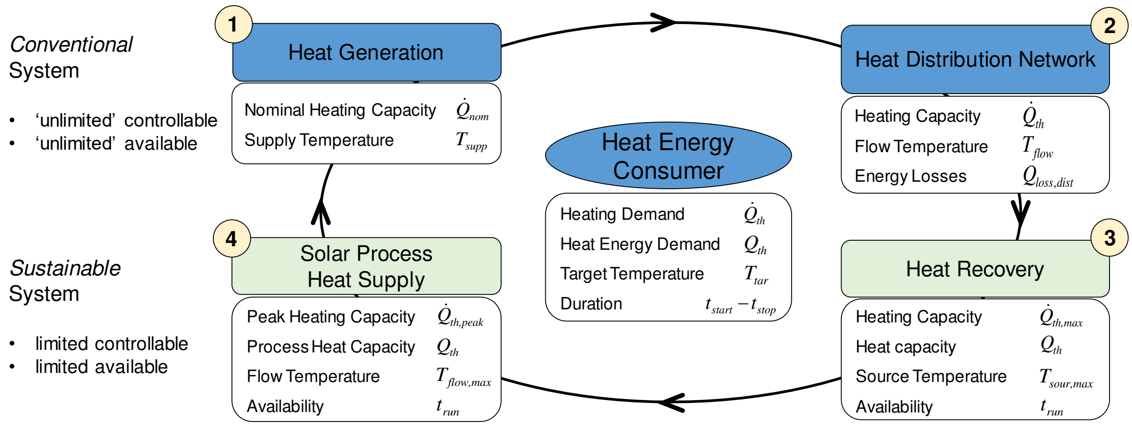

Figure 5.25: Optimisation Circuit

5.1.4 Simulation

The simulation results focus on evaluation of dynamic system behaviour. This is an important additional part of the methodology focusing on development of heat distribution concepts with multivalent heat supply. Modelling and simulation include either parts of or a complete system concept. The effort involved, but also the level of detail of simulations, depends on the simulation tool and hence requires definition of the simulation goal. A simulation-based analysis of each heat source and consumer represents continuation of heat source management.

An objective of this element is an energetic optimised low-grade heat supply with multivalent heat sources, including heat recovery and solar process heat that provides background information for economic evaluation of the SPH-system.

5.1.4.1 Concept modelling

The developed concepts reflect heat distribution systems, using some existing components complemented with new additional components. Systems with a multivalent heat supply (waste heat sources, SPH-system, and conventional backup) and multiple energy consumers lead to high complexity. System analysis, as described in section 3.2 above, provides background for specification of the degree of simulation simplification. Modelling with the modular principle is useful. The developed concept is therefore divided into separate components. Basic elements include a heat source model and an energy consumer model that are individually adaptable. Figure 5.26 illustrates a heat distribution network with several exchangeable heat sources and energy consumers.

Input parameters for heat sources and energy consumers are obtained from energetic analysis (section 0), from analysis of waste heat sources (section 5.1.2.2), and from development of SPH-systems (section 5.1.3.2). These are constant energetic parameters or load profiles. The definition of a simulation period is dependent on time-related heat source availability and on the duration of energy consumption. SPH-systems require a simulation period of one year to analyse system performance with changing irradiation during seasons.

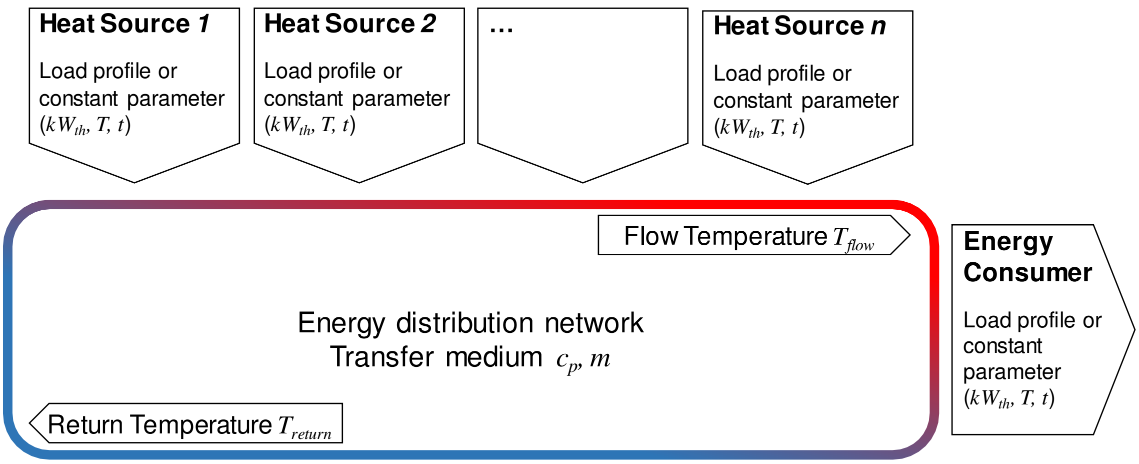

Figure 5.26: Network model with several heat sources

5.1.4.2 Simulation of variations

The simulation of variations starts with validation of a model of components of a real system or of a complete real system. This ensures model behaviour that closely reflects reality and the transferability of simulation results to real-world system configurations. Based on the validated model, the focus is analysis of heat source priority from heat source management (section 5.1.3.3). The structure of the system model with model components therefore enables:

- independent analysis of single heat sources,
- comparison of heat sources, and
- identification of the optimum heat source priority.

Figure 5.27 illustrates preparation and planning of variation simulation. A distinction is made between individual analysis of heat sources and a comparison between two or more heat sources.

Detailed heat source analysis is based on energetic parameters, e.g., heat capacity or course of supply temperature. Existing load profiles from the real system (heat sources and energy consumer) simplify this analysis. The simulation of complete models of heat distribution systems also enables simple variation and optimisation of system parameters, such as flow temperature.

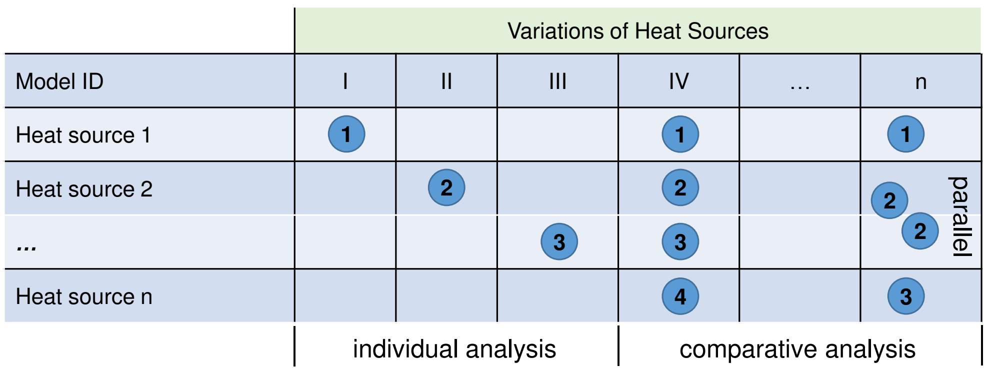

Figure 5.27: Variation and analysis of heat source priority

Energy balances are used for analysis of complete systems. A simulation period that is comparable to that of energy balances of the real system (section 5.1.1.2) enables optimisation analysis with reference to energy demand or GHG-emissions.

5.1.4.3 Optimisation

As described in section 3.3, the development of a system model is a procedure that involves several optimisation loops. The simulation of variations (section 5.1.4.2) analyses available heat sources based on given energetic parameters, producing a final priority list. Favourable sequences of heat sources provide background for optimisation that now focuses on the SPH-system. This sensitivity analysis varies the configuration and aims to maximise solar performance without reducing energy use from waste heat sources.

Parameter definition focuses only on technical feasibility. This enables exclusive validation of energetic issues without economic restrictions. Three system parts produce parameters (Figure 5.27). The collector array provides a high degree of scope for such parameters, including collector area, collector inclination, and orientation. Collector design distinguishes only between flat plate and vacuum tube collectors. The operation parameter is variation in fluid mass flow through the collector. Parameters for storage are, first, storage volume, and then additional insulation, as well as charging and discharging systems.

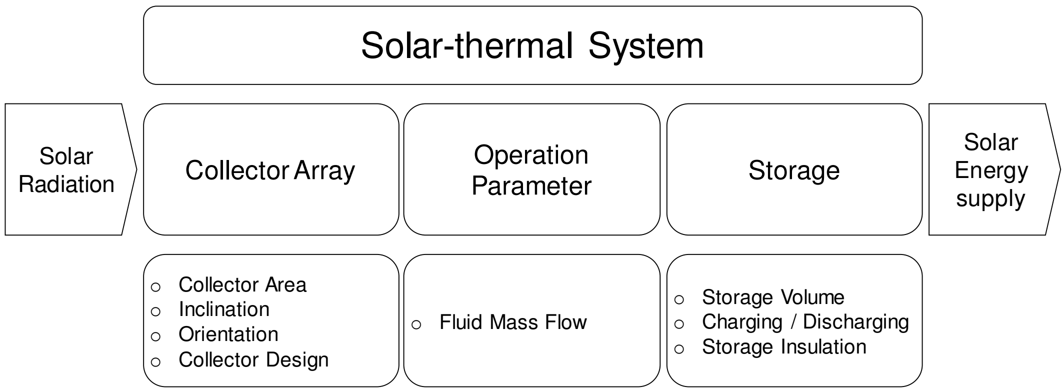

Figure 5.28: Parameters for sensitivity analysis of a SPH-system

Considering parameter variations of the SPH-system, solar efficiency SOL_{eff} (Eq. 5.6) provides background for optimised system performance and is defined as $SOL_{eff,max}$ (Eq. 5.15). The initial equation (Eq. 5.6) is therefore a function of the collector array, operation parameter, and storage:

$$SOL_{eff,max} = f(Colar, Opar, ST) \tag{Eq. 5.15}$$

Economic feasibility study

The final step of optimisation and sensitivity analysis of the SPH-system is evaluation of economic efficiency. The methodology focuses on energetic and technical integration of solar process heat to a heat distribution system that aims to substitute use of fossil fuels. With reference to solar process heat, this means that the economic value of solar heat must be comparable to heat from fossil fuel energy supply units.

The calculation of costs for solar process heat is based on the annuity method (VDI 2067, 2012). This separates all accumulated costs on an annual basis within four subdivisions:

- Capital-related costs (include investment and planning costs);
- Demand-related costs (include electricity for system pumps);
- Operation-related costs (servicing and inspection); and
- Other costs (e. g. insurance; not relevant in this case).

The results of economic efficiency analysis are – in combination with energy from the system – heat production costs.

5.2 Brewery case study

The brewery is an SME with about 80 employees, a turnover of 14 million Euro, and a production volume of about 120.000 hl beer, as well as 60.000 hl non-alcoholic beverages. The brewery is therefore larger than the average brewery in Germany (which would have a production volume of 90.000 hl beer). Company investments focus on production and production technology. Energy supply technology activities are mainly restricted to maintenance. The production manager is also responsible for energy issues, in addition to his primary responsibilities, and therefore has limited capacity to deal with such matters. The company production manager represents the PTEE defined in section 4.5.

A rough assessment with responsible energy engineers at the beginning of the case study confirmed investment in production equipment. Modernisation of the brew house had just been completed and modernisation of filtration was scheduled to start soon. A complete reconfiguration of secondary fermentation was also planned. In contrast to these comprehensive investments in production facilities, energy supply and distribution technology was considered to be of secondary importance. This was particularly obvious in the case of the steam boiler that had already been in operation for 35 years, and that was also too large. This complies with legal requirements but is no longer state-of-the-art. The situation with the chiller system was similar. The proportion of investments in production to energy technology was 20:1 over a period of 10 years. The necessity of investing in energy technology was considered to be dependent on current energy costs, more than on actual energy demand. Low gas prices thus decreased the likelihood of investment in a new efficient gas boiler. The amortisation period for investments in energy technology is 2–3 years, with a mid-term planning period of 3–5 years. The brewery has no official corporate social responsibility initiative. Table 5.11 summarises the important results of these assessment categories.

Table 5.11: Company assessment results

Category	Description
Investment priority	Production equipment
Investment decision	Maintenance first
Energy engineers	Production manager, with limited time to address energy issues
Corporate social responsibility	No official initiative

The analysis below discusses the research question and application of the methodology. It reflects exemplary result of the methodology application within the brewery case study. The detailed results can be found in Appendix B.

5.2.1 Energetic analysis

The brewery does not work with a manufacturing execution system (MES). As a consequence, there is limited availability of process and consumption energy data. This was the most challenging element of methodology application. In contrast, necessary production data were available.

The energy supply company provides energy data, with load profiles of gas and electricity consumption of the company. These data are manually evaluated by energy engineers and are sufficient for compiling an energy balance, as well as for providing specific key figures. Some electricity consumption activities (e.g. for cooling compressors) and electricity consuming areas (e.g., brew house) are recorded manually by technical brewery staff, without load profiles. Heat energy distribution and heat energy consumer energy data are not available (Table 5.12). It is necessary to address these data gaps through temporary data acquisition (Table 5.12); this cannot, however, replace an MES and requires specific equipment. It is additionally time-restricted and limited to select metering points. The brewery has neither the equipment nor the knowledge for such kind of data acquisition and needs assistance by qualified companies.

Available energy data was completed by energy distribution network design documents, as well as through documentation of parameters for production processes and operational parameters of energy units (e.g. cooling system). Insufficient documentation had to be compensated for through insights provided by brewery staff.

Table 5.12: Energy data for energetic analysis

Data level	Data availability	Measure	By
Company	Sufficient	---	---
Heat energy distribution	no	Temporary data acquisition	Qualified company
Heat energy consumer	no	Temporary data acquisition	Qualified company

Finally, compilation of energy data and documentation was sufficient to enable completion of energetic analysis:

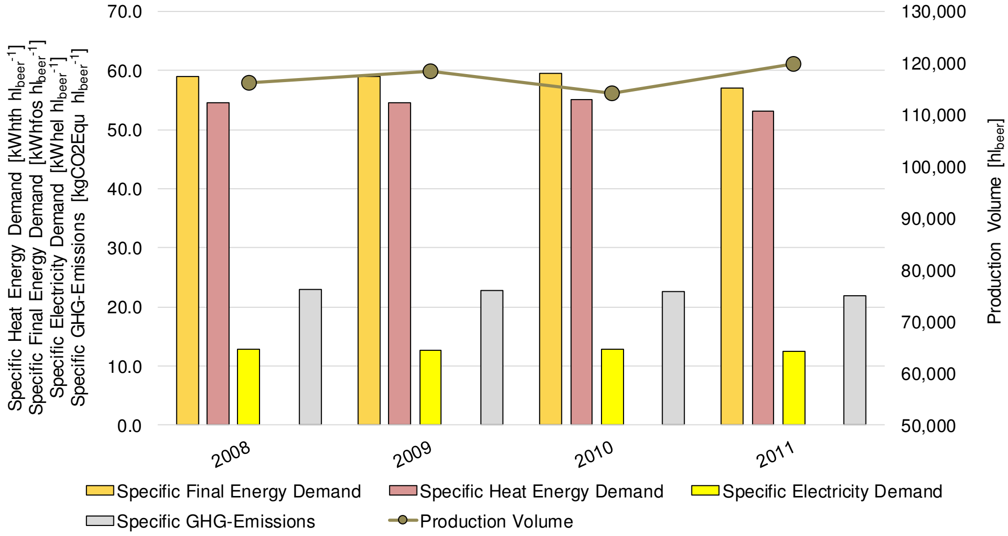

Figure 5.29: Specific key figures and production volume

The energy balance (Figure 5.29) for the defined balance area is easy to understand, providing clear facts regarding the company's energy demand and CO_2-emissions. The defined specific key figures reflect the development of company energy demand and enable energetic benchmarking with industry sector figures (Table 5.13).

Table 5.13: Benchmark of brewery key figures with those of an average brewery with production volume of 250,000 hl_{beer} a^{-1}*

		Average Brewery	Brewery	Deviation
Process Heat	[kWh_{th} hl_{Beer}^{-1}]	48.0	53.0	+ 10 %
Electricity	[kWh_{el} hl_{Beer}^{-1}]	11.4	12.5	+ 9 %

*(Kunze, 2012)

The analysis of energy supply and distribution is based on design documents. The input from brewery staff supports the necessary clarification of the design documents regarding the existing technology. Later optimisation and concept development would be aided by simplification, with a focus on energy supply units and consumers, as well as on energetic parameters of the network.

Table 5.14 shows exemplary the resulting energy supply of the low-grade heat supply. The temperature level of 84°C depends on the supply of the lautering process. The source of this heat supply is heat recovery from wort cooling with 930 $MWh_{th}\ a^{-1}$ in 2010 complemented with heat from the steam energy supply.

Table 5.14: Low-grade heat supply

Energy Supply	Heat Transfer Medium	Temperature Level	Process Heat
Steam Distribution	hot brew water	84°C	1,520 $MWh_{th}\ a^{-1}$
Heat Recovery			930 $MWh_{th}\ a^{-1}$

Division of the brewery into energy-consuming sections clearly indicates the structure of production activities, providing a useful tool (Figure 5.30) that illustrates the energetic characteristics of each section, as well as distinctions between hot and cold areas, and allocation of energy distribution networks. This identifies heat energy-consuming areas, supported with energetic optimisation. The analysis of sections is further important for implementation of solar process heat.

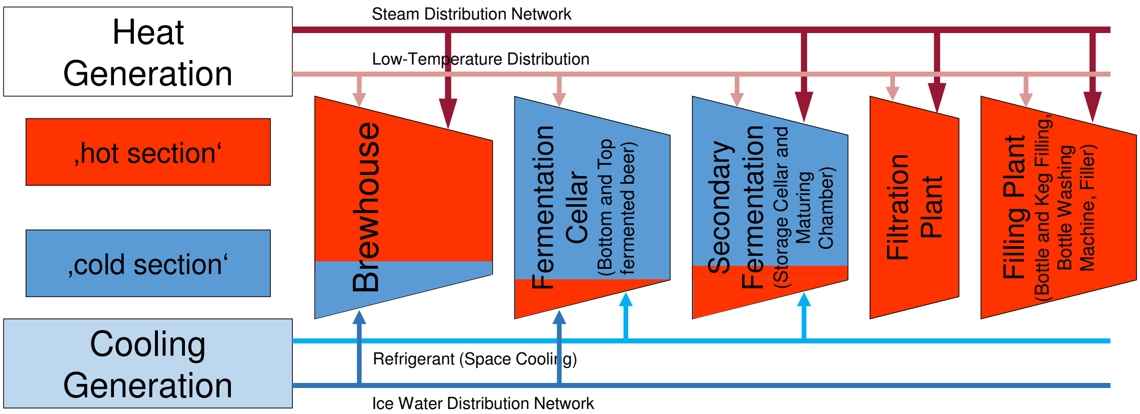

Figure 5.30: Brewery production sections and energy supply

Missing MES data must be compensated for by focused temporary data acquisition of energy consumer load profiles, combined with data relating to energy consumer characteristics. This is very time consuming and requires specific equipment. Running production complicates installation of measuring equipment and additionally limits available measuring points. In consultation with the brewery, data acquisition focused on low-grade energy consumers and on heat recovery sources. A main result produced was the Sankey diagram of the brewery (Figure 5.31). This can be used to complete the energetic analysis.

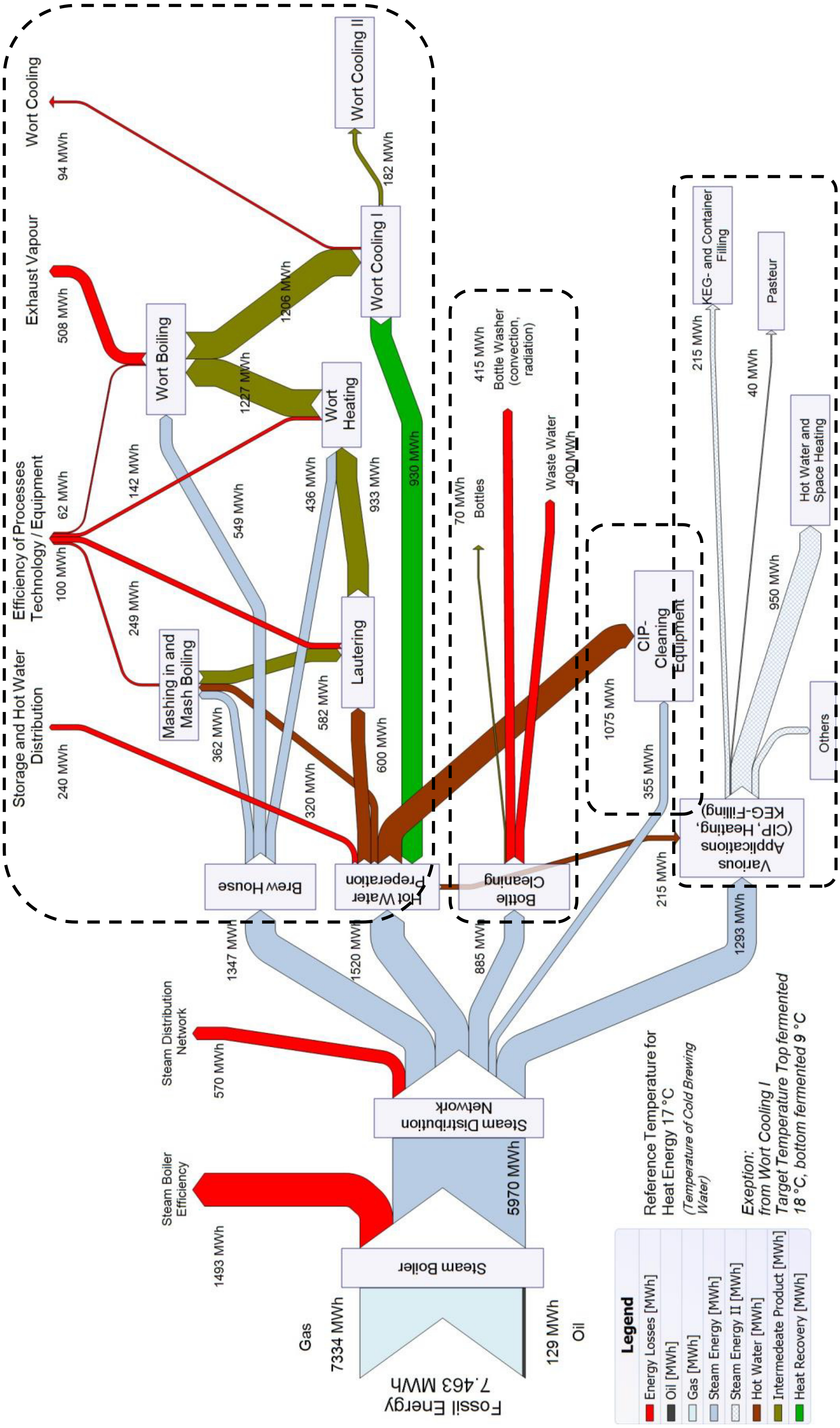

Figure 5.31: Sankey diagram of the brewery

The tools used with this first element can be applied by the brewery PTEE to a large extent (Figure 5.32). Limitations include missing energy data and unavailability of software tools (e.g. for the Sankey diagram). The brewery benefits from complete and detailed energetic analysis. The PTEE will be calculating energy balances with reference to key figures and energetic benchmarks, extending his expertise. The ‘energetic analysis’ element had average function assessment of 38%, requiring only slight support from design engineers.

Function	Tools	Condition(s)	Challenge(s)	Brewery benefit	Tool assessment	Function assessment
Energy Balance	Energy balance	---	---	• More detailed analysis than before • Graphical representation of energy figures	0%	3%
	Specific key figures	---	---	• More detailed analysis than before (over several years) • Analysis of final energy, heat energy, electricity and CO_2-emissions	0%	
	Energetic benchmark	Availability of current industrial sector data	---	• Energetic status of the brewery • Background for internal analysis	10%	
Energy Supply and Distribution	Energetic analysis of energy distribution networks	Continuous data, energy load profiles	Missing (EMS) data	• Analysis of heat energy distribution • Analysis of time related heat capacities	50%	35%
	Analysis of production sections	Production know-how in specific industry sector	Useful section division with energetic background	• Detailed allocation of energy consumption in production sections	20%	
Energy Consumer	Analysis of energy consumer	Continuous data, energy load profiles	Missing (EMS) data	• Time-related analysis with load profiles • Analysis of heat capacity peaks	70%	75%
	Sankey diagram	Expertise in Sankey analysis	Missing Software Tool	• Complete and detailed heat energy flow • Graphical representation	80%	
				Element Average of function assessment	38%	

Figure 5.32: Assessment of energetic analysis with brewery PTEE

5.2.2 Energetic optimisation

The energetic benchmark from energetic analysis provides a general objective of energetic optimisation. Potential for such optimisation must be defined during discussions with the brewery PTEE and brewery staff. In this case, it emerged that comprehensive knowledge regarding specific technologies existed, for example, relating to unused waste heat and its potential. Based on these discussions, the brewery staff was aware of most energetic deficiencies. Documentation that would provide background for a detailed evaluation, however, was often not available and this depended on individual employees’ expertise.

A first essential step for energetic optimisation is evaluating brewery knowledge from documentation and staff. This helps to provide an understanding of the general energetic behaviour of the brewery. The second step is external analysis for an independent view on the energetic status of the brewery and optimisation potential. The combination of brewery knowledge and external analysis provides sufficient background for energetic optimisation of energy supply, distribution, and consumers. The existence of low-grade energy distribution networks is an advantage. Adaption and reconfiguration of existing structures within such a network provides a good basis for optimisation. The existing hot brew water supply (Figure 5.33) represents a low-grade energy distribution network.

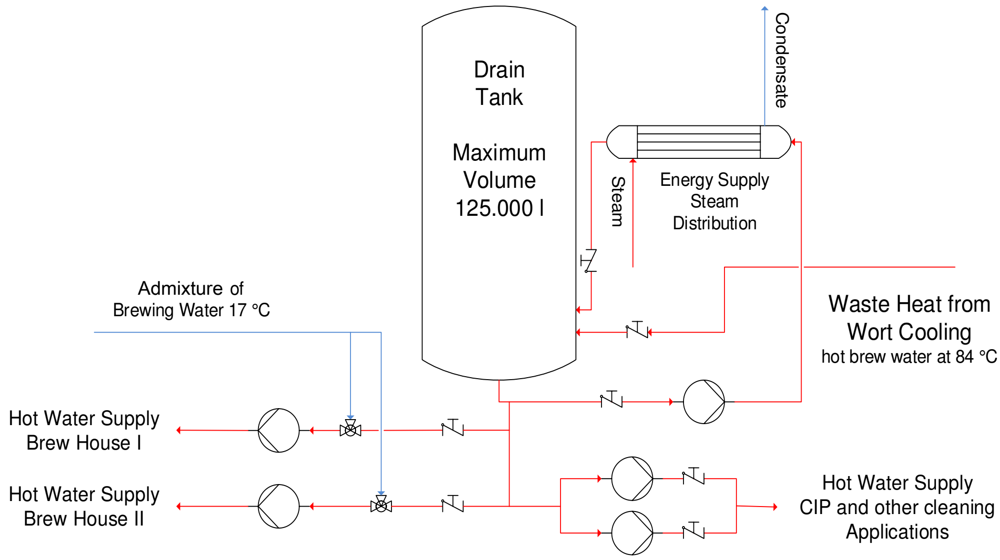

Figure 5.33: Schematic of hot brew water supply

There is optimisation potential from energy supply to that network. This is fossil-generated steam energy that is (besides heat recovery from the wort cooling process) used to supply hot brew water for processes and cleaning. Based on its configuration parameters, this network provides a good platform for waste heat sources. The main energetic optimisation step for substitution of fossil energy involves analysis of waste heat sources and evaluation of their usability. Analysis of unused waste heat is challenging in view of missing energy data. Focused data acquisition must be used to complement knowledge of operational conditions of chiller systems and air compressors, but also of other processes with waste heat potential. Temporary data acquisition only gives limited load profiles, which is a concern given that chiller systems and air compressors vary during operation. Interpolation to longer periods (based on manual data) reduces accuracy but is sufficient for optimisation. Production processes with short durations give an exact load profile. This is all time-consuming but necessary, requiring specific equipment that does not interfere with production. The brewery can assist with this work but does not yet have the necessary experience to conduct this exercise independently.

The input for energy consumers comes from energetic analysis. It is only necessary to verify the suitability of consumers for the low-grade energy distribution network (hot brew water supply). Pinch analysis supports energetic optimisation. As described in section 5.1.2.1, this method was developed for continuous processes with possibility of direct exchange of thermal energy. Its application within the brewery context is complex given the use of batch processes. The two pinch analysis approaches utilised were rescheduling and indirect heat exchange.

Rescheduling aims to change the sequence of processes to reach an optimised possibility of direct heat exchange. On the one side, this means comprehensive intervention in the production philosophy of the plant, and a manufacturing company would therefore need to understand this as a benefit. On the other hand, given the strict sequence of many processes, with use of multiple equipment, the potential for rescheduling in a brewery is limited. The energetic advantages in this case are simply too low. Indirect heat exchange requires integration of heat storage, and decoupling availability of waste heat from heat demand is a second option. This is practicable based on an existing low-grade heat supply with integrated heat storage. As the time event chart illustrates (Figure 5.34), hot streams provide heat energy that can be stored for time-shifted cold streams.

Based on previous analysis, this pinch method can be helpful for energetic reconfiguration of existing low-distribution networks. An exemplary energy balance based on indirect heat supply (using of a drain tank as heat storage) gives Table 5.15. The energy balance for a production day with three brews (Figure 5.34) results a surplus of hot streams, illustrated with a heat recovery rate of 101% without storage losses. However, varying production as well as hot water demand leads to many different cases. The time event chart above and the respectively energy balance is only for a specific case.

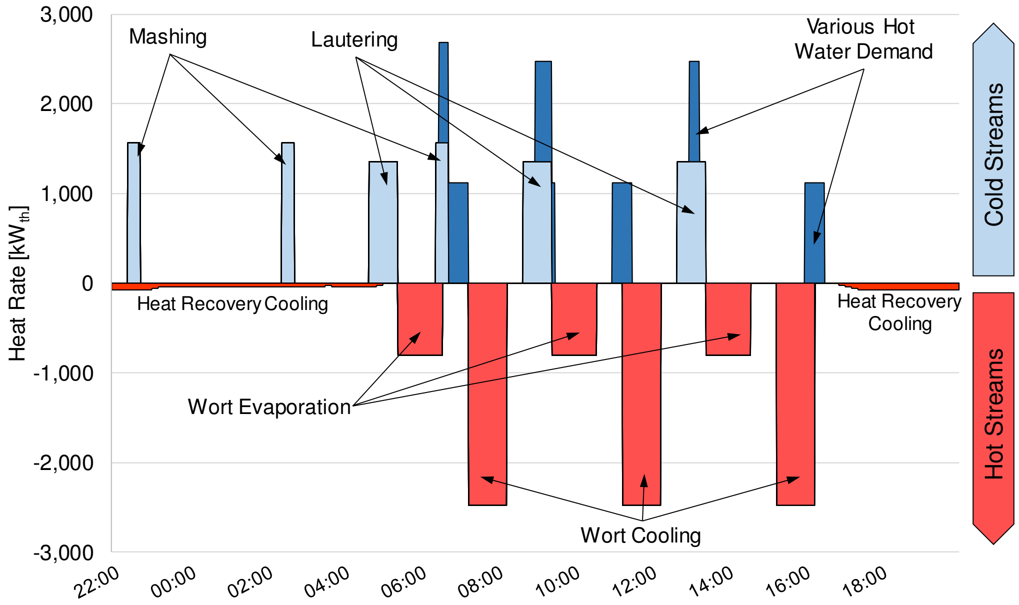

Figure 5.34: Time event chart of low-grade heat supply (example for 3 brews)

Table 5.15: Energy balance low-grade heat supply for 3 brews

	Cold streams	Hot streams
Mashing	2,865 kWh_{th}	
Lautering	4,200 kWh_{th}	
How Water	2,895 kWh_{th}	
Wort Evaporation		2,445 kWh_{th}
Wort Cooling		7,155 kWh_{th}
Heat Recovery Cooling		495 kWh_{th}
Total Energy	9,960 kWh_{th}	10,095 kWh_{th}
Heat Recovery Rate	*~ 101%*	

The analysis of heat distribution networks, individual analysis of heat sources, and analysis of heat energy consumers produces a reconfigured low-grade energy supply (Figure 5.35). Having an existing low-grade distribution network provides favourable background for energetic optimisation.

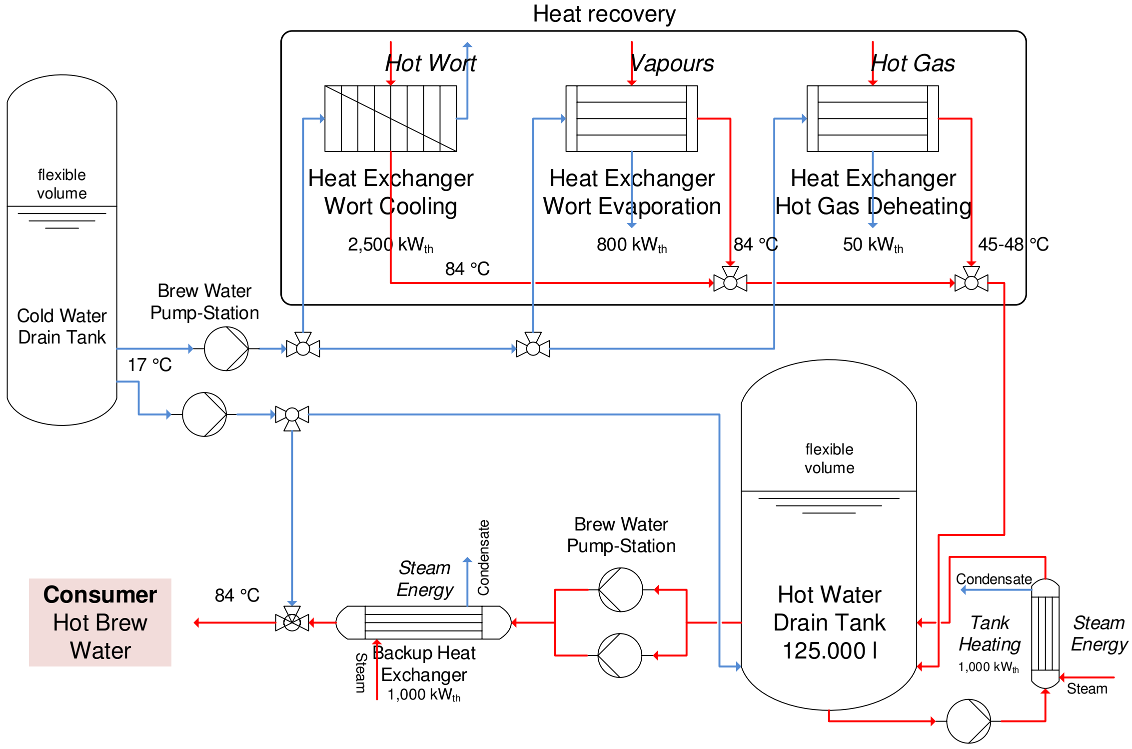

Figure 5.35: Concept of reconfigured and optimised low-grade heat distribution

The energetic optimisation is completed with an energy balance of the concept, with the aim of evaluating the potential for solar process heat supply. This is based on the amount of energy that cannot be covered via waste heat. With analysis, the annual energy demand of the system concept is 2,450 MWh_{th}. The energy balance for the defined LGH-supply (Table 5.16) shows a heat recovery of 1,410.25 MWh_{th}. The remaining steam energy demand is 1,039.75 MWh_{th}. Heat recovery has a fraction of 57.6% and the conventional steam energy of more than 30% lower in comparison to the current system configuration.

Table 5.16: Energy balance low-temperature heat supply concept

	Energy supply	Energy demand
Wort Cooling	1,021 MWh_{th}	
Wort Evaporation	348.8 MWh_{th}	
Hot Gas Deheating	40.45 MWh_{th}	
Steam Energy	1,039.75 MWh_{th}	
Hot Brew Water		2,450 MWh_{th}

Potential for this tool to be applied by the brewery PTEE is more limited in the case of this second element (Figure 5.36). Challenges are again missing energy data and software tools. Brewery PTEE expertise is not sufficient for pinch analysis and for design (reconfiguration) of a low-grade heat supply. This results in an average value of 62% for function assessment. The brewery PTEE thus requires support from design engineers. Benefits for the brewery come from having an independent perspective and from the results obtained.

Function	Tools	Condition(s)	Challenge(s)	Brewery benefit	Tool assessment	Function assessment
Optimisation Potential	Optimisation Potential	Energetic Benchmark and knowledge on industrial sector	Definition of practicable potential	• Definition of general optimisation potential • Energetic classification of the brewery	50%	50%
Heat Recovery	Analysis of waste heat	Knowledge on waste heat sources and load profiles	Missing data (energy load profiles)	• Complete and detailed evaluation of all waste heat sources	50%	65%
	Pinch analysis	Method expertise software	Software necessary and complex use of method	• External view on waste heat recovery • Evaluation of waste heat use	90%	
Concept Development	Reconfiguration / design of low-grade heat supply	Analysis of energy supply networks, energy consumer and waste heat sources	Design expertise required	• New ideas for low-grade heat distribution • Complete design concept for low-grade heat supply	70%	70%
				Element Average of function assessment	62%	

Figure 5.36: Assessment of energetic optimisation with brewery PTEE

5.2.3 Solar process heat system

The background for the design of an SPH-system stems in part from the configuration parameters of low-grade heat supply; this refers both to already integrated heat sources as also to thermodynamic network conditions (flow and return temperature, heat capacity). Additionally, the definition of existing components (e.g., heat storage) provides input. Furthermore, the amount of energy from energetic optimisation that can be covered with solar process heat enables a first determination of SPH-system size, while simultaneously indicating maximum possible size. The system matrix (Figure 5.19 in section 5.1.3.2) is the main tool for basic configuration of the SPH-system. Its use requires expertise in SHP-system design. Assistance from the brewery helps in defining user expectations; these are an important aspect of system design and must be considered. The second methodological tool for SPH-system design is the evaluation matrix for analysis of company buildings and defines the useful area for collector mounting. The evaluation criteria are simple to use. Important assistance provided by the brewery during this stage includes provision of information on structural building parameters, and also information about planned new buildings or changes to existing buildings. Results include, not only the maximum collector area on buildings, but also the spatial distribution of relevant equipment (e.g. heat storage) and possible integration points of solar process heat with low-grade distribution in comparison to collector mounting areas. Decisions regarding use of building areas remain, however, at the discretion of the brewery.

All the data provide sufficient input for development of a design concept of an SPH-system that is adequate for simulation. Detailed SPH-system design requires expertise from system suppliers, in cooperation with specific design engineers.

Heat source management is the final methodological tool of this element and provides a priority list of heat sources:

- The optimised sequence of heat sources is first transferred to the concept for low-grade heat supply developed with energetic optimisation. This provides the integration point for solar process heat and minimises negative interactions between sources.
- Subsequently, results feed into development of the simulation model and the simulation.

The tool can be applied simply by just using the constant heat source parameter. Ignoring load profiles of the various heat sources, however, results in inaccuracy. This demands with an increasing number of heat sources a simulation. This is the case for the SPH-system as it depends not only on the conditions of the heat distribution network, but also on specific irradiation at a location.

The third element requires expertise relating to SPH-systems (Figure 5.37) and tools. This is not available at the brewery and it is only just possible for the PTEE to assist with the process.

Function	Tools	Condition(s)	Challenge(s)	Brewery benefit	Tool assessment	Function assessment
Application Potential	Solar Potential	Relevant location data (irradiation) and expertise in SPH-systems	Rough estimation of specific collector earnings	• Background information for decision-making - basis for system size - determination of solar heat supply	100%	100%
System Configuration	System configuration with design matrix	Expertise in SPH-system design	System design regarding heat distribution and energy consumer	• Background information for decision-making - Recommendation of system design	100%	88%
	Roof evaluation	Knowledge on the method and relevant building data	Sufficient knowledge on roof structure	• Background information for decision-making - determination of useful area	75%	
Heat Source Management	Heat source management	Availability of heat source data	Focus on energetic parameter	• Background information for decision-making - priority list of heat sources	70%	80%
	Redesign of low-grade heat supply with solar process heat	Prepared low-grade heat supply concept from energetic optimisation	Configuration of multivalent heat supply	• Background information for decision-making - concept of low-grade heat supply	90%	
				Element Average of function assessment	89%	

Figure 5.37: Assessment of solar process heat system with brewery PTEE

With average function assessment of 89%, this element is thus only useable when there are design engineers with specific background in SPH-systems. PTEE input is necessary for roof evaluation and heat source management; the latter also provides information that is independent of the SPH-system to the brewery, extending energetic knowledge. Benefits for the brewery include final decision-making information for design of an LGH-supply with integrated SPH-system.

5.2.4 Simulation

The simulation was carried out using MATLAB&Simulink (The Mathworks, 2010) and the toolbox CARNOT (Hafner B. et al, 1999). This simulation tool provides an advanced level of individual modelling but is complex in application and requires very specific expertise. This applies not only to modelling, but also to simulation and in particular, to the evaluation of simulation results.

Individual modelling enables component-based development of the simulation model. It is possible to simulate and evaluate each heat source both independently and in combination with other heat sources (Figure 5.38). The simulation results of each heat source model can be verified against real data. This ensures further transferability of simulation results from the system model (concept of complete low-grade heat supply) to the real world.

	Variations of Heat Source Configuration					
Model ID	con bw	hr 1	hr 1	hr 3	solar bw	solar bw + hr
Solar-Thermal Energy					●	●
hr Wort Cooling	●	●	●	●	●	●
hr Wort evaporation		●		●		●
hr Cooling System			●	●		●
Steam Energy before storage	●	●	●	●	●	●
Backup (Steam Energy) after storage	●	●	●	●	●	●

Figure 5.38: Heat source configurations of low-grade heat supply

Table 5.17 compares exemplary the energy balances of ID solar bw and ID solar bw + hr. It results a disadvantage influence of heat recovery on the solar process heat source. Configuration ID solar bw + hr supplies therefore 22% less solar energy to process than ID solar bw. This finding clarifies the direct correlation of prior heat recovery and subordinate solar process heat. A reduced energy supply to causes higher storage temperatures in the solar thermal system and has unfavourable effects on the energy losses.

System simulation can essentially confirm the priority list of heat sources but also the interaction between heat sources. This is a first for the SPH-system. Its performance depends direct on the sequence of other heat sources and is limited by them. Sensitivity analysis of the SPH-system shows some optimisation potential, with collector type or direction, and inclination of collector areas.

As described before, the simulation of heat supply systems with multivalent heat sources is a complex task and requires comprehensive know-how. This is not available at the brewery.

The energetic results of the simulation are input into the energy balance. In final analysis, this enables improvement via energetic optimisation and integration of solar process heat with low-grade heat supply. The focus is thereby on reduction of fuel-based energy and CO_2-emissions. This analysis can confirm the energetic optimisation potential of the second methodological element.

Table 5.17: Energy balance LGH-supply with heat recovery and SPH-system

Energy Source		**ID con bw**	**ID solar bw**	**ID solar bw + hr**
Solar Energy from *collector area*	MWh_{th}	---	704.5	576.5
Energy losses from *storage and piping*	MWh_{th}	---	58.8	73.3
Solar Energy to *Process*	MWh_{th}	---	645.6	503.2
hr Wort Cooling	MWh_{th}	1,024.9	1,024.2	1,014,8
hr Wort Evaporation	MWh_{th}	---	---	362,4
hr Cooling Chiller	MWh_{th}	---	---	68.2
hr Total	MWh_{th}	1,024.9	1,024.2	1,445.4
Steam energy *Brew Water feed*	MWh_{th}	1,383.3	739.7	459.7
Steam energy *Backup*	MWh_{th}	63.2	64.3	56.3
Energy Demand Hot Brew Water	MWh_{th}	2,471.4	2,473.8	2,464.6

An economic feasibility study completes the simulation and focuses on the SPH-system. The defined method (VDI 2067, 2012) is commonly used at manufacturing companies and enables both application and discussion of findings. Despite satisfying solar earnings of the SPH-system, economic feasibility was found to be low and the amortisation period did not correspond to brewery conditions.

This final element requires specific expertise in system simulation and simulation tools (Figure 5.39). In this case, average function assessment was 76%, as this knowledge was not available at the brewery. The PTEE can only assist with modelling and evaluation of simulation results. Software tools are not available; neither is simulation expertise. However, the energy balance and economic evaluation (depending on available SPH-system costs) can feasibly be carried out, to a large extent, by the PTEE. The main benefit for the brewery is having simulation-based evaluation of a reconfigured LGH-supply.

Function	Tools	Condition(s)	Challenge(s)	Brewery benefit	Tool assessment	Function assessment
Modelling of Concept	Component Modelling	Availability of data, expertise in system modelling and simulation (tool)	Sufficient heat source and energy consumer load profiles for model validation	• Simulation based analysis of real world system components	100%	100%
	System Modelling	Validated components, expertise in system modelling and simulation (tool)	Development of a system model with transferable results to the real world	• Simulation based analysis of real world low-grade heat supply - heat sources - energy consumer	100%	
Simulation of Variations	Simulation of Variations	Functional basis system model		• Comparison of variations of heat source sequence • Add or remove energy consumer	90%	90%
Optimisation	Sensitivity Analysis (SPH-system)	Knowledge of relevant optimisation parameter	Definition of technical feasibility optimisation (transferable to the real world)	• Optimised SPH-system	100%	100%
Evaluation	Energy balance	Input of energetic data from simulation	---	• Effects of energetic optimisation • Reduction of fossil fuel consumption • Reduction of CO_2-Emissions	0%	15%
	Economic evaluation of SPH-system	Energetic results of simulation, system costs, expertise in economic evaluation method	Determination of system costs	• Background for decision-making • Input for investment planning • Input for strategic planning	30%	
				Element Average of function assessment	76%	

Figure 5.39: Assessment of simulation with brewery PTEE

5.3 Dairy case study

The dairy is a LE with about 1,100 employees. The company processes about 440,000 tons of milk and has a turnover of 850 million Euro. It is among the ten leading dairies in Germany. The dairy can be classified as a modern and innovative milk processing company. There is significant investment in energy efficiency and production equipment. A separate department is responsible for all company energy matters. One main objective of the department is continuous improvement of energy efficiency. There is thus adequate capacity among department employees for this topic, and these represent the FTEE defined in section 4.5.

A rough assessment of the dairy carried out with responsible energy engineers at the beginning of the case study reflects the investment activities. Besides ongoing modernisation of production equipment, the dairy invests large sums in waste management and in sustainable energy supply. This includes a CHP operated with biogas from the dairy's own waste water treatment plant. The proportion of waste heat used in process heat supply is about 13% and is continuously being improved. The dairy also decommissioned its own fossil-fired steam boiler and obtains process heat from a biomass CHP (Zott, 2015). Investment decisions were made with company-defined amortisation periods. The dairy has a comprehensive corporate social responsibility policy, including production from raw material to finished product stages, as also environment and work force-related initiatives.

Table 5.18: Important assessment results

Category	Description
Investment priority	production and energy equipment
Investment decision	amortisation period
Energy engineers	company department for energy issues
Corporate social responsibility	available (Zott, 2015)

The analysis below discusses the research question and application of the methodology. It reflects exemplary result of the methodology application within the brewery case study. The detailed results can be found in Appendix C.

5.3.1 Energetic analysis

The dairy works with an MES for control of production processes. Permanent measurement equipment records data relating to energy distribution networks and energy consumers. This comprehensive database was helpful and facilitated analysis.

The energy supply companies of the dairy provide energy data with load profiles for steam energy and electricity consumption. Continuous evaluation of company energy data by the energy department (FTEE staff) provides optimal background for development of energy balances and specific key figures. The data recording carried out by the dairy includes:

- energy provided to the company from external supplier,
- heat distribution networks (steam and LGH),
- electricity consumption (air compressors and chiller systems), and
- various energy-consuming processes (e.g. CIP).

It was not necessary to acquire additional data for energetic analysis (Table 5.19). Temporary data acquisition was only necessary to refine the data for further detailed analysis of specific consumers of interest (e.g., air compressors, to analyse the cooling circuit regarding waste heat potential). The dairy even has both necessary equipment and FTEE staff with required knowledge.

Table 5.19: Energy data for energetic analysis

Data level	Data availability	Measure	By
Company	Sufficient	---	---
Heat energy distribution	Sufficient	---	---
Heat energy consumer	Sufficient	---	---

Design documents of the distribution networks can be obtained from the MES. These range from layout plans to detailed drawings of single heat supplies and distribution equipment. The MES also provides documentation of production process parameters and operational energy unit parameters. This was advantageous and saved time.

Table 5.20 gives the exemplary energy balance from the dairy case study. The availability of detailed energy data at the dairy enables their detailed analysis: Since 2009, the biomass-fired power plant with an additional gas-fired peak load steam boiler supplies the dairy with steam energy. The dairy steam boilers are only in operation during standby of the biomass plant. Hence, the primary energy sources of biomass and fossil fuels are only considered in connection with GHG-emissions. These includes the emissions of fossil fuels used for steam boiler and the fuels used at the CHP-Plant as well as the emissions for electricity. In contrasts to steam energy, process heat represents the total process heat demand including heat recovery.

The energy balance is basis for the specific key figures shown in Figure 5.40. It is for the entire dairy and gives specific energy demand as well as CO_2-emissions, based on milk processing volume.

Table 5.20: Energy consumption and GHG-emissions

		2008	2009	2010	2011
Gas*	[MWh]	64,500	48,246	-	-
Heating Oil*	[MWh]	-	6,927	703	1,038
Steam CHP-Plant	[MWh_{th}]	-	8,278	61,355	62,039
Steam Energy	[MWh_{th}]	55,875	56,940	61,975	62,955
Process Heat	[MWh_{th}]	-	60,490	69,681	70,679
Electricity	[MWh_{el}]	47,565	48,101	51,752	49,888
GHG-Emissions	[to_{CO2Equ}]	43,849	42,693	36,814	36,936

* used only for dairy steam boilers

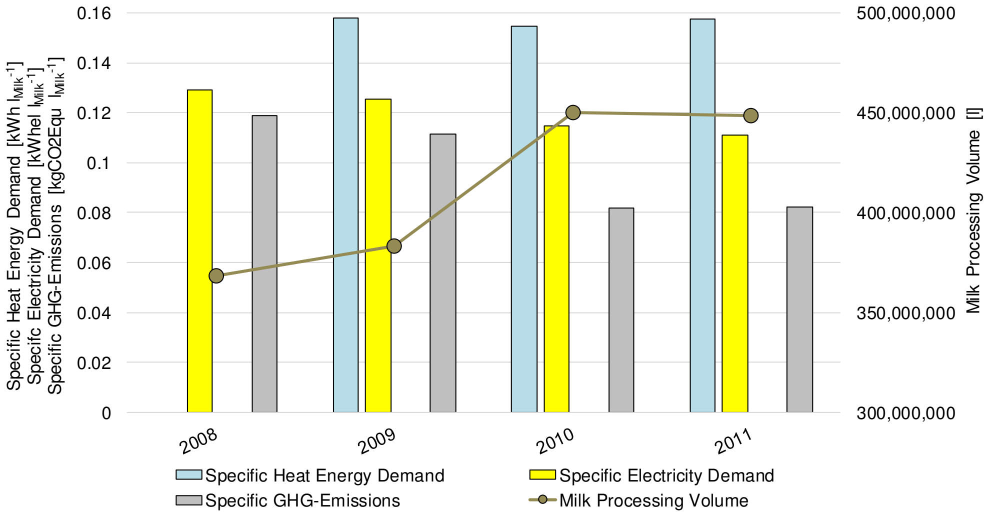

Figure 5.40: Development of specific key figures

Benchmarking of dairy key figures must be conducted against more general key figures of the dairy sector (Table 5.21). This is a disadvantage as the energy demand of dairies varies significantly in relation to production portfolios; such figures are not available. However, specific key figures provide a useful indicator for a company to have internal control of possible improvements.

Table 5.21: Benchmark of key figures*

		German Dairies	Case Study Dairy	Deviation
Process Heat	[$kWh_{th}\ l_{Milk}^{-1}$]	0.02–0.18	0.158	- 12%
Electricity	[$kWh_{el}\ l_{Milk}^{-1}$]	0.01–0.13	0.111	- 15%

*(EnergieAgentur.NRW, 2012)

The MES system of the dairy enables further a comprehensive analysis of the different energy supply networks. Table 5.22 illustrates the parameter of the low-grade heat network. This network supplies 6,868 MWh_{th} a^{-1} (2011) at a supply temperature of 65°C with water as heat transfer medium.

Table 5.22: Low-grade heat network

Energy Generation	Heat Transfer Medium	Temperature Level	Process Heat
Heat Recovery + Steam Boiler	Water	65°C	6,868 MWh_{th} a^{-1}

The MES provides the energy data with a step range of 15 minutes. This allows additional to the energy balances a detailed analysis of the load profiles. Figure 5.41 shows an exemplary load profile of the low-grade heat network heat capacity.

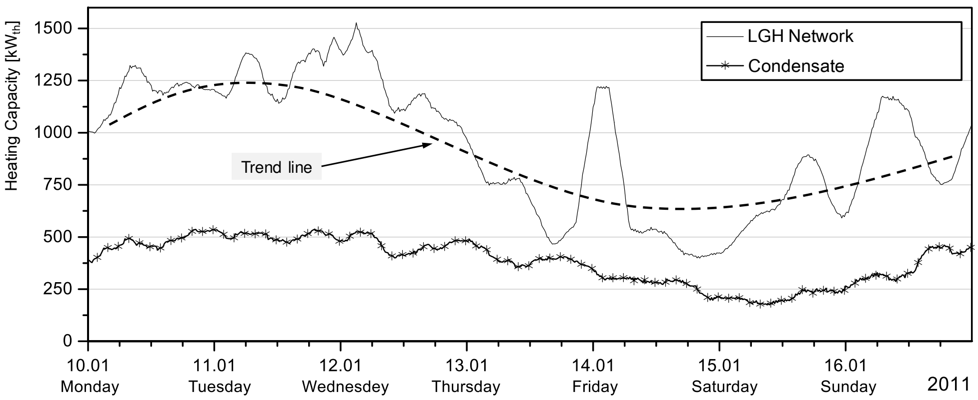

Figure 5.41: Exemplary weekly load profiles for LGH-network in winter

Table 5.23 shows the electricity consuming networks for cooling and pressurised air. The chiller provide with a propulsion energy of 5,708 MWh_{el} a^{-1} (2011) about 21,366 MWh_{th} a^{-1} of cooling energy. The air compressors need 5,567 MWh_{el} a^{-1}.

Table 5.23: Cooling distribution and pressurised air

Energy Generation	Heat Transfer Medium	Temperature Level	Propulsion Energy
Chillers	Ice Water	0–1°C	2,573 MWh_{el} a^{-1}
Chillers	NH_3	-3°C	3,135 MWh_{el} a^{-1}
Compressor	Air	-	5,567 MWh_{el} a^{-1}

This was a more complex system than the brewery, because of the amount of different products, the manifold steps of processing from raw milk to finished products, and the size of the dairy. Although comprehensive design documentation of all relevant systems and processes was available, division of the dairy into energy-consuming sections was nevertheless very helpful (Figure 5.42).

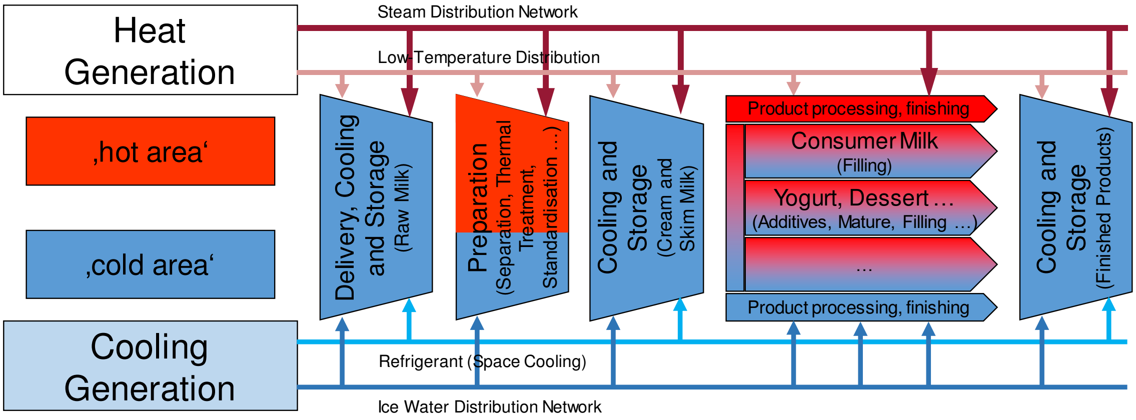

Figure 5.42: Dairy Production Sections and Energy Supply

The analysis of heat distribution networks resulted in an existing LGH-network that was designed on the basis of specifications given by the energy department's FTEE. The network had already been reconfigured several times for different waste heat sources. The current network parameters and heat sources provide a promising background for integration of additional waste heat and solar process heat. This existing heat distribution system demonstrates the expertise of the energy department and confirms a continuous process of improvement at the dairy. This also means that energy consumers are connected to the network (Table 5.24).

Table 5.24: Configuration of heat consumer

	Target Temperature T_{tar}	Heating Capacity $\dot{Q}_{th,\max}$	Duration t_{dur}
Production	> 60 °C	525 kW_{th}	
CIP	> 60 °C	1750 kW_{th}	0.5–2 h
Hot water	60 °C	830 kW_{th}	cont.
Space heating	24 °C	1000 kW_{th}	as required

These, in combination with a low flow temperature, ensure maximum use of available waste heat at any heat. The heat supply to consumer groups CIP and production is therefore designed as a two-stage heat supply, with the LGH-network first and steam energy second.

The dairy FTEE has the necessary expertise to apply the tools of the first element (Figure 5.43), with an assessment average of 13%. The dairy nevertheless benefits from independent analysis and from exposure to new ideas of a design engineer. Another benefit is more detailed analysis of data and its preparation. Even where there is a dedicated energy department, this is often not possible because of lack of time.

Function	Tools	Condition(s)	Challenge(s)	Dairy benefit	Tool assessment	Function assessment
Energy Balance	Energy balance	---	---	• Independent analysis and data preparation	0%	3%
	Specific key figures	---	---	• Independent analysis and data preparation • Comprehensive analysis of CO_2-emissions	0%	
	Energetic benchmark	Availability of current industrial sector data	Individuality of dairy key figures regarding production programme	• Energetic status of the dairy	10%	
Energy Supply and Distribution	Energetic analysis of energy distribution networks	Continuous data, energy load profiles	---	• Independent analysis of the network configuration • More comprehensive data analysis and preparation	5%	13%
	Analysis of production sections	Production know-how in specific industry sector	Useful section division with energetic background and complexity of the dairy	• Alternative kind of production analysis with the defined sections	20%	
Energy Consumer	Analysis of energy consumer	Continuous data, energy load profiles	---	• Independent analysis and data preparation	5%	23%
	Sankey diagram	Expertise in Sankey analysis	Missing Software Tool	• Complete and detailed heat energy flow • Graphical representation	40%	
				Element Average of function assessment	13%	

Figure 5.43: Assessment of energetic analysis with dairy FTEE (energy department)

5.3.2 Energetic optimisation

Benchmarking of the dairy via energetic analysis confirmed that there is already good energetic status, in comparison to the wider industrial dairy sector. The analysis of key figures over the years also confirmed continuous improvement in relation to specific energy demand and CO_2-emissions. An assessment of further optimisation potential with the dairy FTEE, however, revealed some additional unused waste heat sources. These already feature in future energy efficiency planning. The high level of company expertise was particularly favourable in this case; in combination with independent expertise from design engineers, this enables useful optimisation and reconfiguration of heat supply and distribution. This means that the dairy FTEE is not only part of the optimisation process, but is also an active player in its co-design. Combined knowledge of dairy and energy technologies is therefore especially valuable.

The dairy operates, via the LGH-network, a system that provides promising background for integration of solar process heat. Further development of the network will occur according to the energetic strategy of the dairy energy department. The network has good conditions for waste heat integration, in part a result of the work of the energy department of the dairy. At any one time, at least one energy consumer group of the LGH-network requires energy. The consequence is continuous operation of the network and a continuous demand for heat energy supply. In contrast to the brewery (section 5.2.2), this enables direct waste heat integration.

The dairy has all required data for analysis of available unused waste heat sources. Temporary data acquisition serves to provide additional and detailed information on the quality of waste heat (e.g., temperature load profile of cooling circuit of air compressors). Using original pinch analysis requires steady conditions of heat supply and heat use. However, all load profiles of LGH-networks vary (both energy consumers and waste heat sources). It is therefore necessary to define specific load conditions and apply pinch analysis for specific small periods of time. This is possible as all load profiles of the dairy show a similar course and depend on milk processing volume.

The energy distribution network and waste heat analysis (using the pinch method) were input for LGH-network reconfiguration (Figure 5.44). With the support of the dairy FTEE, two configurations were produced. In comparison to the brewery, the existing LGH network is more favourable for energetic optimisation.

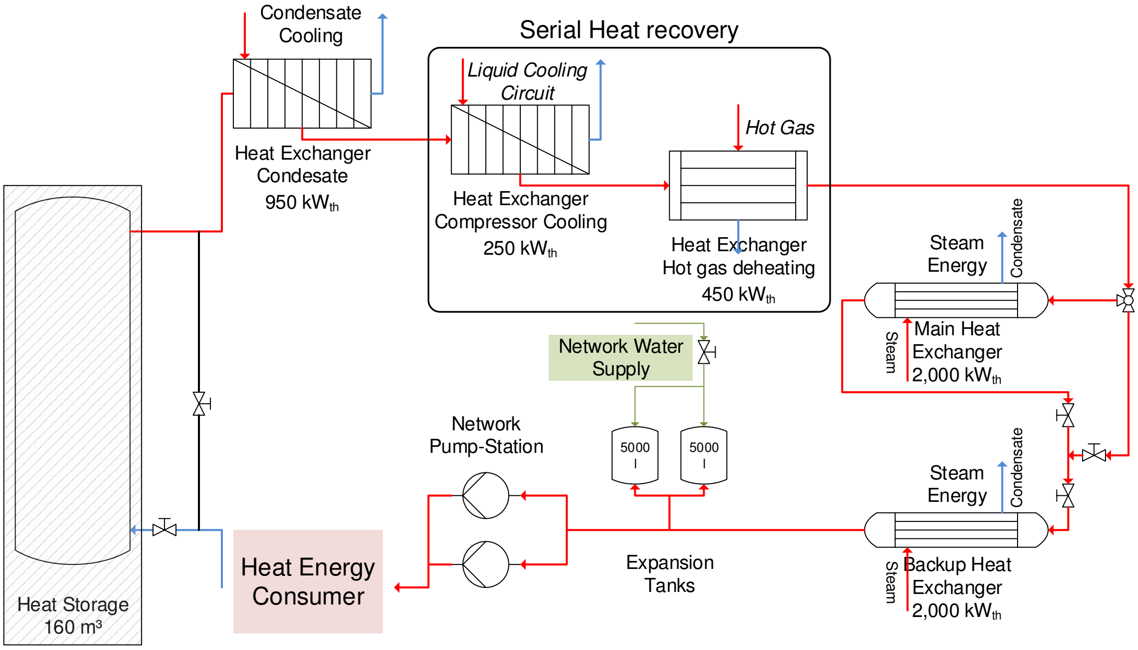

Figure 5.44: Concept LGH-network with serial heat recovery

The balance of heat recovery potentials and current heat supply to the low-grade heat supply in Table 5.25 completes energetic optimisation. This indicates an amount of energy that cannot be met by waste heat and provides input for design of the SPH-system.

Table 5.25: Heat recovery potential of LGH-network (2011)

		Heat recovery	LGH-network
Chiller	$hr_{ch,energy}$	1,027 MWhth	
Air Compressor	$hr_{ca,energy}$	867 MWhth	
Condensate Energy	Q_{th}		3,387 MWhth
Steam Energy	Q_{th}		3,481 MWhth

The tools of the second element can be applied, to a large extent, by the dairy FTEE (Figure 5.45). Required energy data are recorded by the dairy; the staff's comprehensive measurement equipment expertise enables additional temporary data acquisition. Pinch analysis, being a very specific method, is primarily responsible for the element average of 40%. This cannot be applied with the dairy FTEE's knowledge, since necessary software is missing. The dairy energy department has broad expertise in the design of LGH-networks. External support by design engineers, however, provides alternative solutions for optimisation and is considered a main benefit.

Function	Tools	Condition(s)	Challenge(s)	Dairy benefit	Tool assessment	Function assessment
Optimisation Potential	Optimisation Potential	Energetic Benchmark and knowledge of industrial sector	Definition of practicable potentials	• Independent analysis: – general optimisation potential – energetic classification of the dairy	30%	30%
Heat Recovery	Analysis of waste heat	Knowledge of waste heat sources and load profiles	---	• Independent analysis: – load profiles waste heat – evaluation of waste heat sources	30%	50%
	Pinch analysis	Method expertise software	Software necessary and complex use of method	• External view of waste heat recovery • Alternative evaluation of waste heat use	70%	
Concept Development	Reconfiguration / design of low-grade heat supply	Analysis of energy supply networks, energy consumer and waste heat sources	Design expertise required	• New / alternative design concept for LGH-network	40%	40%
				Element Average of function assessment	40%	

Figure 5.45: Assessment of energetic optimisation with dairy FTEE (energy department)

5.3.3 Solar process heat system

The initial situation for design of an SPH-system was comparable to that of the brewery (section 5.2.3) and included:

- Configuration parameters of the LGH-network, with flow and return temperature and heat capacity (load profiles of energy supply from the network and to the network),
- An analysis of existing components (e.g. heat storage) for use in a reconfigured LGH-network, and
- The amount of heat energy from energetic optimisation that can be covered with solar process heat.

The expertise of dairy FTEE relating to SPH-system design was the same as at the brewery. Staff could therefore assist in the process, using the system matrix (Figure 5.19 in section 5.1.3.2) for basic configuration of the SPH-system. The dairy FTEE further supports application of the evaluation matrix for assessment of the maximum useful collector mounting area in the same way as at the brewery. Continuous work to improve the energetic behaviour of the dairy provides important background for analysis of existing components. Even if a component (e.g. heat storage) is currently unused, there are possible ideas for new usage.

Detailed SPH-system design requires, not only the expertise of the system supplier, but also cooperation with planning engineers. The dairy FTEE can assist more comprehensively with reference to the integration point of solar process heat to the network and the use of existing equipment.

Previous analysis of waste heat sources by the dairy feeds into heat source management. This means increased application of the methodological tool and consequently increased influence on the result of heat source management. It demonstrates the high level of expertise of relevant energy topics. Tools such as heat source management, with a structured evaluation procedure, can therefore complement the dairy FTEE's expertise for specific areas of responsibility.

The result is a concept for the low grade heat supply. Figure 5.46 illustrates a simplified sequence of heat sources to the concept. The integration of the SPH-system is in focus and based on the reconfigured low-grade heat supply from energetic optimisation. The approach defines an integration point for solar process heat after heat recovery. The interdependence of heat recovery and solar thermal heat supply is a major aspect of the further system analysis with the simulation.

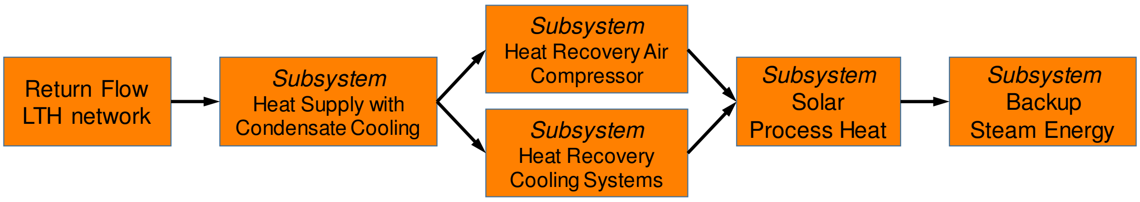

Figure 5.46: Subsystem Structure Low-Temperature Heating Network with Heat Recovery and Solar Process Heat

Results of the assessment of tools and measures used with the third element are comparable to those obtained at the brewery (Figure 5.47).

Function	Tools	Condition(s)	Challenge(s)	Dairy benefit	Tool assessment	Function assessment
Application Potentials	Solar Potential	Relevant location data (irradiation) and expertise in SPH-systems	Rough estimation of specific collector earnings	• Background information for decision-making – basis for system size – determination of solar heat supply	100%	100%
System Configuration	System configuration with design matrix	Expertise in SPH-system design	System design regarding heat distribution and energy consumer	• Background information for decision-making – Recommendation of system design	100%	88%
	Roof evaluation	Knowledge of the method and relevant building data	Sufficient knowledge of roof structure	• Background information for decision-making – determination of useful area	75%	
Heat Source Management	Heat source management	Availability of heat source data	Focus on energetic parameter	• Independent analysis: – priority list of heat sources – alternative ideas of waste heat use	50%	60%
	Redesign of low-grade heat supply with solar process heat	Prepared low-grade heat supply concept from energetic optimisation	Configuration of multivalent heat supply	• Independent analysis: – LGH-network configurations – alternative perspectives • Background information for decision-making	70%	
				Element Average of function assessment	83%	

Figure 5.47: Assessment of solar process heat system with dairy FTEE (energy department)

The dairy FTEE can just assist with the process, giving an average function assessment of 83% for this element. FTEE input is first necessary for roof evaluation and heat source management. Heat source management also provides SPH-system independent information. The dairy ultimately benefits from the design of low-grade heat supply with integrated SPH-system, but also through provision of background information for decision making.

5.3.4 Simulation

The simulation tool is the same as for the brewery (section 5.2.4). Its flexibility and use of component-based modelling enable the transfer of model blocks from the brewery case study to the dairy case study. Individual parameterisation configures the blocks for each application case.

The variation of heat sources is therefore comparable (Figure 5.48 and Figure 5.49) and confirms usability as well as a standardised procedure. The completeness and range of energy data from the dairy, combined with analysed load profiles and configuration data of the network, provide sufficient basis for verification. This ensures further transferability of simulation results from the system model (concept of complete low-grade heat supply) to the real world.

	Variations of Heat Source Connection				
Model ID	ac	cs	ac-cs	cs-ac	ac+cs
Condensate Energy	1	1	1	1	1
hr Air Compressor (ac)	2		2 serial	3 serial	2 parallel
hr Cooling System (cs)		2	3	2	2
Steam Energy	3	3	4	4	3

Figure 5.48: Heat recovery *hr* source configurations of LGH-network

	Variations of Heat Source Connection	
Model ID	st	ac+cc-st
Condensate Energy	1	1
hr Air Compressor (ac) / ***hr*** Cooling System (cs)		2
Solar-Thermal Energy (st)	2	3
Steam Energy	3	4

Figure 5.49: Heat source configurations of LGH-network with heat recovery *hr* and solar-thermal energy *st*

Table 5.26 compares exemplary the results of the annual simulation.

Table 5.26: Simulation results of variations with solar-thermal energy

Energy Source		**ID st**	**ID ac+cc-st**
Condensate Energy	MWh_{th}	3,458.5	3,458.5
hr Air Compressor	MWh_{th}	---	278.0
hr Cooling Chiller	MWh_{th}	---	753.5
Solar Energy from *collector array*	MWh_{th}	677.0	611.3
Solar Energy to *LGH-network*	MWh_{th}	520.5	449.7
Steam Energy	MWh_{th}	3,052.6	2,046.3

System ID st supplies 677 MWh_{th} solar process heat from the collector array to the storage and 520.5 MWh_{th} heat energy from the storage to the LGH-network. The configuration of parallel heat recovery and SPH-system after that (ID ac+cc-st) results in lower solar process heat supply. The energy yield from the collector array is with 611.3 MWh_{th} about 10% lower compared to system ID st. The energy supply to LGH-network is at 450 MWh_{th} and even 13.5% lower than without heat recovery (ID st). This illustrates the interdependence of waste heat and solar process heat supply as competing heat sources.

There is no expert simulation knowledge available at the dairy. It is therefore even more important to discuss the simulation results with the FTEE. Staff input regarding dairy processing and specific heat supply requirements is important for simulation-based optimisation and helpful for all levels of simulation, including the following:

- Verification of the LGH-network simulation model (base configuration as for current operation) as background for further simulation;
- Detailed assessment of variations in heat source connections; and
- Results and optimisation (sensitivity analysis) of the SPH-system integrated to the LGH-network.

Element simulation is completed via the energy balance, with simulation results, and the economic feasibility study of the SPH-system.

The simulation element (with its tools) requires specific expertise as well as simulation tools that are also not available at the dairy (Figure 5.50). Function assessment average is 70%, just slightly lower than at the brewery. The support of the dairy FTEE is limited to assisting with modelling and evaluation of results. Energy balance assessment and economic evaluation (depending on available SPH-system costs) can feasibly be carried out by the FTEE. The benefit for the dairy is having a reconfigured LGH-network, analysed via simulation of several heat source variations.

Function	Tools	Condition(s)	Challenge(s)	Dairy benefit	Tool assessment	Function assessment
Modelling of Concept	Component Modelling	Availability of data, expertise in system modelling and simulation (tool)	---	• Simulation based analysis of real world system components	100%	100%
	System Modelling	Validated components, expertise in system modelling and simulation (tool)	Development of a system model with transferable results to the real world	• Simulation based analysis of real world low-grade heat supply – heat sources – energy consumer • Complements dairy knowledge	100%	
Simulation of Variations	Simulation of Variations	Functional basis system model	Definition of heat source variations feasible with real world systems	• Comparison of variations of heat source sequence	70%	70%
Optimisation	Sensitivity Analysis (SPH-system)	Knowledge of relevant optimisation parameter	Definition of technical feasibility optimisation (transferable to the real world)	• Optimised SPH-system • Background information for decision-making	100%	100%
Evaluation	Energy balance	Input of energetic data from simulation	---	• Effects of energetic optimisation • Reduction of fossil fuel consumption • Reduction of CO_2-Emissions	0%	10%
	Economic evaluation of SPH-system	Energetic results of simulation, system costs, expertise in economic evaluation method	Determination of system costs	• Background for decision-making • Input for investment planning • Input for strategic planning	20%	
				Element Average of function assessment	70%	

Figure 5.50: Assessment of simulation with dairy FTEE (energy department)

5.4 Case study summary

The case study summary discusses the research questions (section 2.9) and case study application of the methodology. It is therefore necessary to consider the results obtained and application of element functions with tools and measures. It is also important to focus on cooperation with the brewery PTEE and the dairy FTEE.

5.4.1 Essential functions of the methodology

The first research question concerns the essential functions of the methodology for design and implementation of a process heating system. A function is essential for the methodology if the user needs detailed instructions for its application. In contrast, a function is important (more or less so) if the user has the necessary expertise for its application. This, however, does not mean that such a function can be left out, as it is still necessary for completeness of the methodology and to meet the objective of SPH-system integration.

The case studies discussed above, and especially the prior assessment of elements, provide a basis for answering this question. Figure 5.51 compares function assessments (green frame) for each case study (section 5.2 and 5.3), giving the resulting function assessment average (red frame).

A first result of this assessment relates to differences between the two case study applications, illustrating the influence of available background energy knowledge on methodological application. A broader and larger knowledge base leads to lower requirements for support from external experts (e.g., design engineers). The energy department of the dairy has more staff that is exclusively responsible for technical and energetic topics, providing an advantage over the brewery, where the PTEE is also (and primarily) responsible for production. This needs to be considered within the context of methodological application.

The main results relate to essential functions and are defined by two criteria:

- The function assessment average is 45% or higher.
- The case study function assessment is 65% or higher.

This considers both the average of the case studies and individual methodology application within case study companies. For such a function, the applicant (company with its PTEE or FTEE staff) would therefore require instruction regarding the proposed methodology, as knowledge is insufficient.

Average functions of element ‘energetic analysis’ are less important. Except for the energy consumer function within the brewery case study, this was the same for all functions. This confirms that there is comprehensive background energetic analysis for both case study companies; the required methodological knowledge is therefore available.

Energetic optimisation functions are also generally less important but have clearly higher assessment values. This illustrates lower company expertise in energetic optimisation in comparison to energetic analysis. Heat recovery and concept development are essential for the brewery. As a result, concept development is also essential for the average value of the function assessment. The results of the two case studies clearly differ. In these specific application cases, this is as a consequence of the different distribution of tasks among responsible staff.

Despite heat source management for the dairy case study and evaluation of both case studies, all element functions of ‘solar process heat systems’ and ‘simulation’ are considered to be essential. SPH-systems are a specific heat supply technology and are not common in either industrial sector. This results in low design expertise of responsible staff. Simulation is not exclusively useful for SPH-systems but is nevertheless not popular at either case study company. Simulation expertise is considered a service and is commissioned if necessary for decision-making. An exception is the economic efficiency study, based on a method that is standard in all companies and that only needs to be adapted to the specific case.

Element	Function	Function assessment Case Study brewery		Function assessment Case Study dairy		Function assessment Average		Function Proportion	
Energetic Analysis	Energy balance	3%	38%	3%	13%	3%	25%	*1*	*0,21*
	Energy Supply and Distribution	35%		13%		24%		*4*	
	Energy Consumer	75%		23%		49%		*5*	
Energetic Optimisation	Optimisation Potential	50%	68%	30%	40%	40%	54%	*2*	*0,23*
	Heat Recovery	65%		50%		58%		*5*	
	Concept Development	90%		40%		65%		*4*	
Solar Process Heat System	Application Potential	100%	89%	100%	83%	100%	86%	*3*	*0,26*
	System Configuration	88%		88%		88%		*4*	
	Heat Source Management	80%		60%		70%		*5*	
Simulation	Modelling	100%	76%	100%	70%	100%	73%	*5*	*0,30*
	Simulation of Variations	90%		70%		80%		*3*	
	Optimisation	100%		100%		100%		*4*	
	Evaluation	15%		10%		13%		*2*	
								47	*1*

Figure 5.51: Comparison of function assessment with the case study results

Figure 5.52 shows the revised structure of the proposed methodology, with functions not defined as essential shown with a blue coloured background. The assessment of functions illustrates that the methodology needs to start with detailed instructions regarding function heat recovery. This is the stage at which companies need support from design engineers, with confirmation of decreasing expertise with each function (Figure 5.52). However, case studies also confirmed the need for conscientious use of each function as a basis for implementation of an SPH-system.

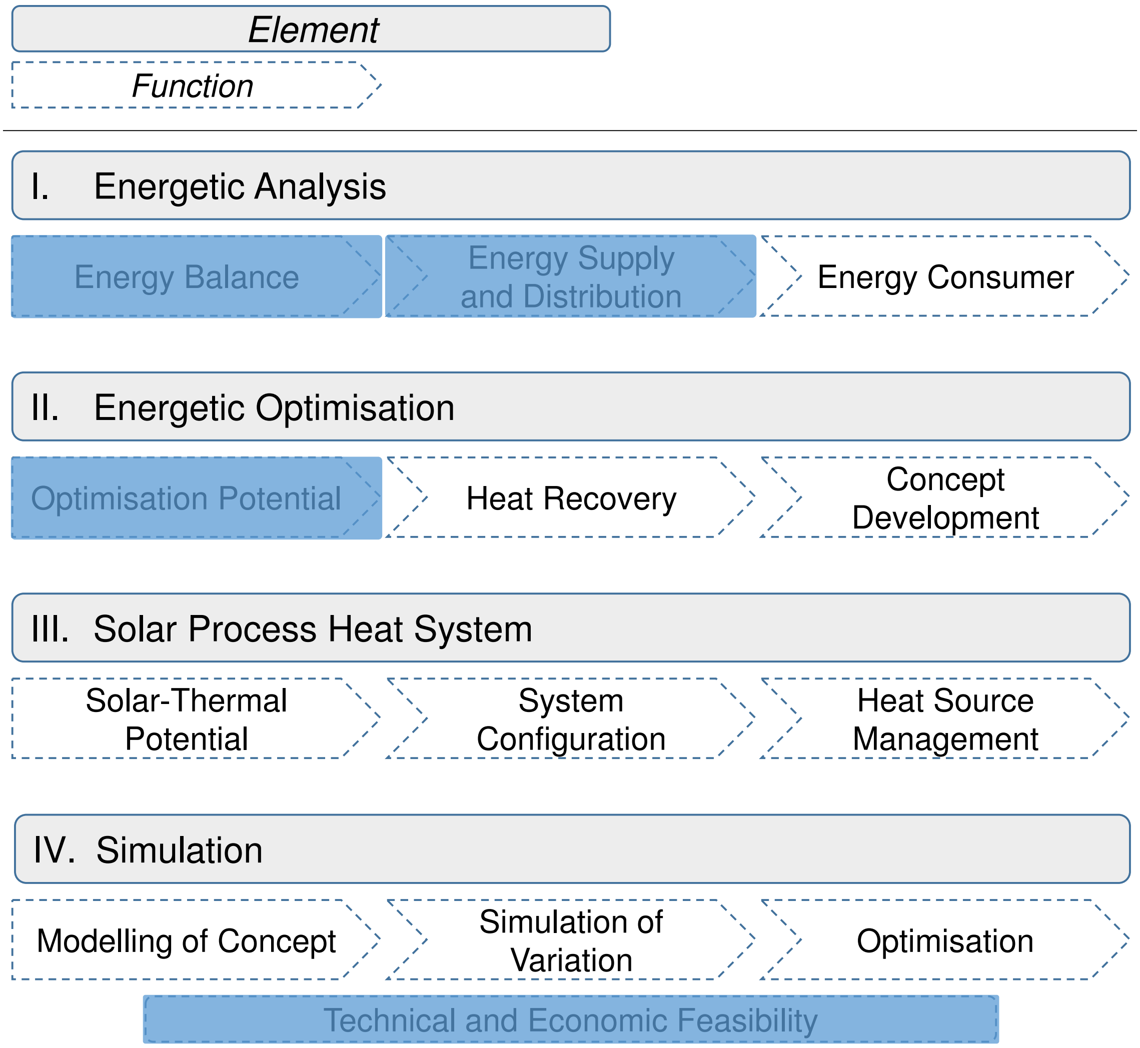

Figure 5.52: Revised structure of the proposed methodology

The case studies finally provide conclusions regarding different proportions of time and effort required for the functions. These aspects need to be evaluated with reference to function proportion. A value of 1–5 is therefore defined for each function. The sum of functions of one element divided by the sum of all functions gives the proportion for an element. (Eq. 5.16) illustrates an example function proportion (FP) for energetic analysis (EA). This ultimately reflects the proportion for each element within the methodology (*Function Proportion* in Figure 5.51). However, this does not determine whether a function is essential or not:

$$FP_{EA} = \frac{(1+4+5)}{47} = 0{,}21 \quad \text{(Eq. 5.16)}$$

5.4.2 Methodology usability and flexibility for energy engineers

The second research question focused on development of a methodology that provides a platform with good usability and flexibility to support energy engineers in the design of cost-effective solar process heat systems:

- Usability in this case is defined as having functions that can be easily understood (good learnability) and used by energy engineers, with their available knowledge. Hence, use of the function can enhance company expertise.
- Flexibility means, on the one hand, that the functions can be adapted to various uses within the defined application area. On the other hand, it is advantageous if the methodological elements can be used independently from each other (for example, a company already works with an optimised LGH-network and can directly start with the solar process heat system element).

Application of the methodology at the brewery and dairy provided input to help answer this second research question. The following evaluation is consequently a result of application of the methodology, in cooperation with case study companies, and reflects feedback provided on all functions (and related tools) by the energy engineers.

Both EMs (as company representatives) define economic efficiency as a major decision-making criterion for energy supply systems, emphasising the importance of cost-effective system design. Of course, this measure depends on individual company policy and can differ between companies. The proposed methodology uses a standard method for economic evaluation; this method is well known within industry, has high usability, and satisfies the company requirement for a purely economic evaluation of SPH-systems with amortisation period.

Usability

Figure 5.53 gives the usability of methodology functions. The usability valuation is within a range of 1–5, where 5 is maximum usability and 1 is minimum usability.

Element	Function	Usability
Energetic Analysis	Energy balance	5
	Energy Supply and Distribution	5
	Energy Consumer	4
Energetic Optimisation	Optimisation Potential	5
	Heat Recovery	4
	Concept Development	3
Solar Process Heat System	Application Potential	2
	System Configuration	3
	Heat Source Management	4
Simulation	Modelling	1
	Simulation of Variations	1
	Optimisation	2
	Evaluation	4

Figure 5.53: Function usability

Energetic analysis and energetic optimisation requirements are in agreement, in many respects, with the working method of energy engineers and confirm high usability. Apart from pinch analysis (a complex tool with specific software requirements) for heat recovery, the application of the tools can enhance company expertise. For example, key figures from company internal analysis and industry-sector benchmarks, as well as Sankey diagrams, were transferred to companies' tool boxes. These tools are easy to learn, in contrast to the pinch method. Consequently, companies are able to analyse their energy use in a more detailed and comprehensive manner, giving better background for decision-making regarding energy efficiency measures.

Another situation illustrates the usability of solar process heat systems and simulation elements. Design and integration of an SPH-system requires specific expertise but also has similarities with other process heat technologies. Prior knowledge of energy engineers hence leads to partly good usability (e.g., heat source management). However, system simulation has low usability, as this is not part of the standard requirements of energy engineers. Despite the fact that a company is not able to implement these elements on its own, system simulation and its results have high value for decision-making, as confirmed by energy engineers. Even participating in the process of system simulation and in analysis of simulation results can therefore contribute to enhancing company expertise.

Methodology usability is hence high for energetic analysis and energetic optimisation, but decreases in the case of solar process heat systems and simulation.

Flexibility

The proposed methodology was applied at a brewery and dairy with comparable energy systems and with similar requirements for LGH-networks as a basis for SPH-systems. These conditions are transferable to other food industries (section 2.2) and represent similar use cases. The application of the methodology to the two case studies therefore shows sufficient flexibility. Flexibility is additionally linked to independent use of the elements. Each element of the methodology therefore needs to be self-contained, requiring input (e.g., energy data) and providing a result (e.g., system concept for LGH-network).

The approach was to analyse application of each element independently. The application of the methodology to the two case studies confirms this element independence (Appendix B and Appendix C), as described in the following examples:

- Previous energetic analysis conducted by the dairy energy department makes it to possible to start directly with the energetic optimisation element.
- The ‘energetic optimisation’ element provides an optimised LGH-network concept that can be implemented independently from other elements.
- The ‘simulation’ element can be carried out on the basis of ‘energetic analysis’ and ‘energetic optimisation’, focusing only on heat recovery. The ‘solar process heat system’ element is therefore not necessary.

This independence applies, not only to complete elements, but also to single functions or tools, as described in the following examples:

- Specific key figures are very useful for energetic benchmarking and for internal analysis, as confirmed by energy engineers. These can be used completely independently of the methodology. Both companies use these as standard analysis tools.
- Heat source management was also developed for use independently of the methodology, as it aims to first provide a priority list of heat sources. The dairy, for example, is able to do this using available expertise relating to energetic analysis and optimisation.

The flexibility of the methodology was therefore confirmed.

5.5 Comparison of the developed methodology with existing SPH-guidelines

This research deals with development and case study application of a methodology (chapter 4) for SPH-system design and integration. One objective is to fill gaps and improve inadequacies of existing SPH-guidelines, as analysed in section 2.6.2. These incomplete SPH-guidelines were compared with the structure of the developed methodology to verify whether this objective was met.

In addition to SPH-guidelines, industry specific concepts (section 2.6.3) provide a similar procedure for analysis and optimisation of energy supply systems with implementation of renewable energy systems. The developed methodology shall hence also be compared against these industry-specific concepts.

5.5.1 Comparison with industry-specific concepts

As analysed in section 2.6.3, industry-specific concepts propose the very ambitious goal of CO_2-free thermal energy supply. A top-down approach is developed for the food industry and requires comprehensive reconfiguration of the heat supply system. Additionally, an upgrade of production equipment is necessary. In addition to substantial investment, a consequence is intervention in production. This high standard limits application of industry-specific concepts to a small group of companies.

The developed methodology, in contrast, guides companies step by step with a bottom-up approach to analyse and optimise the heat supply system, increase energy efficiency, and integrate solar process heat. This supports energy savings and reduction of CO_2-emissions. The focus is on low-grade heat supply and not on a specific industry sector. Flexible application of the methodology (section 5.4.2) enables individually defined objectives and is applicable to a wide range of industries. Furthermore, this methodology allows the users to play a role in system design, whereas industry-specific concepts do not.

Similarities between the author's methodology and industry-specific concepts are limited to energetic analysis procedures and, in part, to the procedure for energetic optimisation with reconfiguration of the heat supply system.

5.5.2 Comparison with SPH-guidelines

The main purpose of the developed methodology is to guide company energy engineers and system designers in the design and integration of SPH-systems for industrial heat supply. This has been demonstrated with case studies, and applied in cooperation with companies and their energy engineers. As noted in section 5.4, an essential part of methodological development is analysis of usability, based on the feedback of energy engineers. This was not done for existing SPH-guidelines (section 2.6.2).

A second purpose of the methodology was to provide a complete guide for the process, spanning energetic analysis to evaluated SPH-system design. The intention was to fill gaps left by insufficiencies in existing SPH-guidelines, as analysed in section 2.6.2. This required:

- completing insufficient features of existing SPH-guidelines, and
- defining (as well as adding) missing features of existing SPH-guidelines.

Figure 5.54 therefore compares recommendations of Sopro (2012), Schmitt, (2012), and TU Wien (2013), analysed within the literature review (section 2.6.2), against the elements and functions of the proposed methodology of this thesis:

- A partly red function of the proposed methodology indicates optimisation (completion and more detail) of an insufficiently-developed feature from existing SPH-guidelines.
- A fully red function of the proposed methodology indicates a new feature that completes existing SPH-guidelines.

<u>New features (elements and functions in the author's own approach)</u>

Figure 5.54 demonstrates, first, the completion of existing SPH-guidelines with element 'simulation'. Simulation is essential, as described in section 5.4.1. This

requires expert knowledge and specific software tools but provides detailed information that provides important background for decision-making. This includes simulated results of energetic behaviour of designed heat supply systems. In turn, simulation results provide important input for economic evaluation. Another useful aspect of simulation is the possibility of optimisation without real world experiments. The final results of simulations are optimised system configurations that are transferable to the real world.

Heat source management developed for this methodology also completes a gap in the SPH-guidelines. Existing SPH-guidelines point to the importance of heat recovery and recommend maximum use of waste heat but do not provide a tool for energetic comparison. This is similar to the situation for optimisation potential, which includes a general energetic assessment of the company. In general, SHP-guidelines do not provide tools for user application.

Addressing inadequacies of SPH-guidelines

The methodology developed by the author includes functions and procedures that are comparable to some of the features of existing SPH-guidelines. Examples are the function called 'energy consumer' within the element called 'energetic analysis' or the function called 'system configuration' within the element called 'solar process heat system' (Figure 4.2). Analysis of comparable features within other methodologies allowed these functions to be developed within the methodology of the author. The significance of each function as well as the usability and flexibility of the methodology are evaluated within the case studies through the analysis of user feedback (section 5.4).

Furthermore, there are functions (such as energy balance of energetic analysis or concept development of energetic optimisation) that also feature in existing SPH-guidelines. As shown in the analysis of literature review results (section 2.6.2), these features are, however, insufficiently developed. The developed methodology hence completes these functions, improving the level of detail and completing missing aspects. Case study application and user feedback confirmed that this methodology can guide company energy engineers and system designers step by step, from basic analysis to development of an optimised heat supply system with solar process heat.

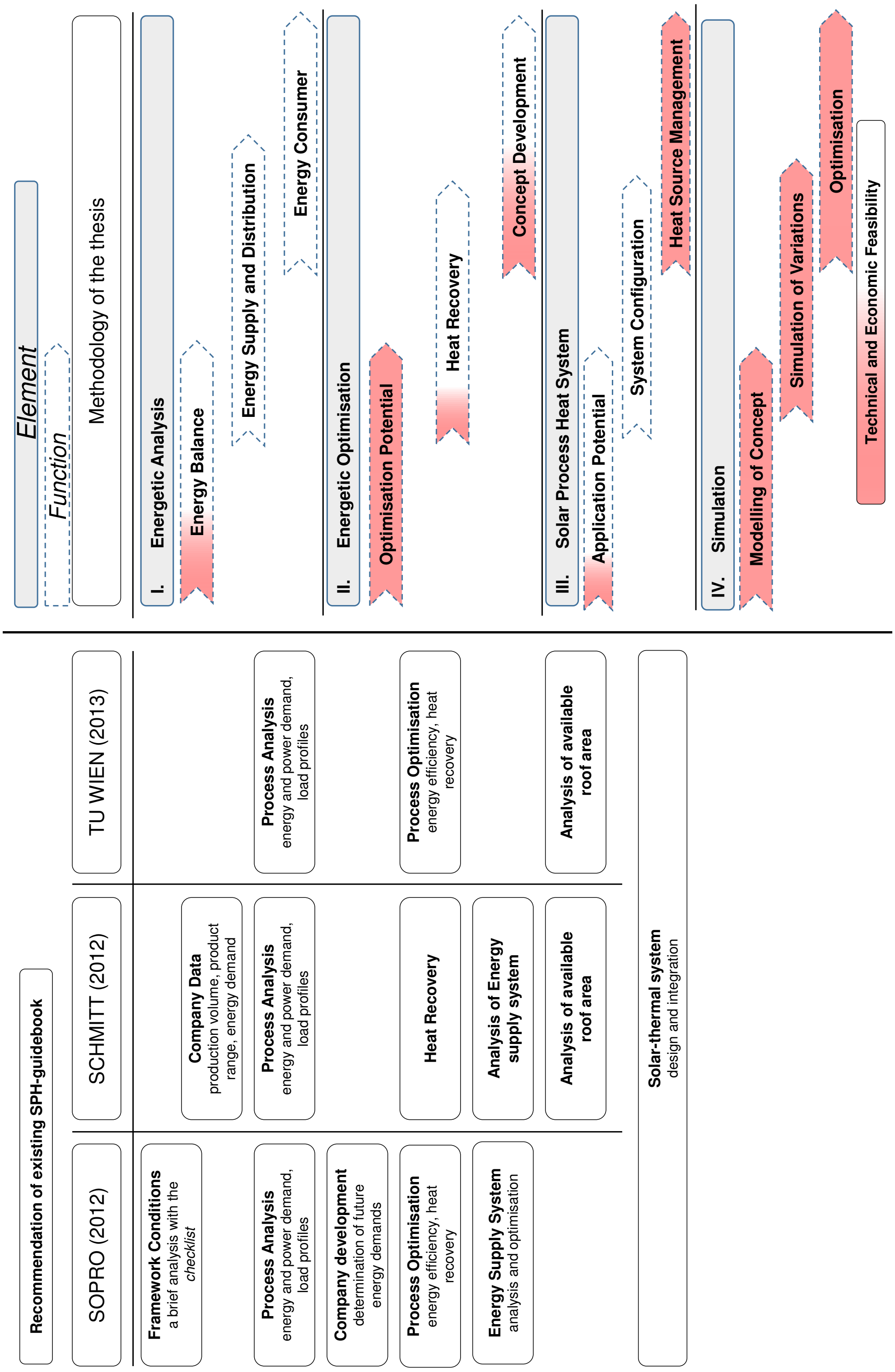

Figure 5.54: Methodology comparison

6 Conclusions and outlook

The objective of this research was to develop a methodology that guides system designers and company energy engineers in the process of integrating solar thermal heating systems within process heat systems of food and drink companies. The methodology is intended to support companies' efforts to save energy and reduce CO_2-emissions associated with low-grade heat supply systems. This is demonstrated by the simulation results of the case studies:

- The optimised low-grade heat supply of the brewery with increased heat recovery and solar process heat resulted in 1,592.5 MWh less final energy use than the original system. This means a reduction of 65% and reduces CO_2-emissions of the brewery by 12.5%.
- The final energy demand for the comparable dairy system was reduced by 41% what means 2,816 MWh. In contrast to the brewery, CO_2-emissions were reduced by only 2.3%.

These results of methodology application demonstrate promising optimisation potential for low-grade heat supply. However, the meaning of low-grade heat varies between companies, leading to different original systems. The brewery, for example, covers 35% of process heat demand with low-grade heat, in contrast to the dairy, that only covers 10% with low-grade heat. Reasons include the established company structure (location of production equipment and energy units) or the individual focus on heat supply technologies. This complicates the definition of general potential for improvement of energy efficiency in this area. Significant differences between reductions in CO_2-emissions also depend on the fuel that is used for heat supply before optimisation (gas at the brewery, mainly wood at the dairy).

An essential goal for methodology design was usability by energy engineers. The case study application therefore commenced with a draft methodology and then involved the user in the process of developing a final methodological design. This enhanced usability.

The literature review in chapter 2 analysed different methodologies for analysis, optimisation, and reconfiguration of heat supply with implementation of solar process heat systems. These include standards for energy audits, guidelines, and research into energy efficiency and solar process heat systems, as well as industry-specific concepts.

Existing guidelines for solar process heat provide a good basis for development of a methodology. Detailed analyses, however, show that existing SPH-guidelines have gaps and are insufficiently developed (section 2.6.2). Industry-specific concepts include similar procedures with regard to integration of renewable energy systems. These concepts, however, deliver CO_2-free heat supply. This is a very challenging goal that demands comprehensive reconfiguration of energy supply systems and production equipment, consequently requiring significant investment and production interventions. Application of the concept is therefore limited. There is therefore ultimately no existing methodology that adequately considers user needs.

The developed methodology provides a complete procedure for integration of solar process heat systems for industrial heat supply. The general approaches of increasing energy efficiency, saving energy, and reducing CO_2-emissions enable flexible application. Case studies and the collection of user feedback improve usability of the methodology. This was demonstrated with the two case study companies and evaluated in section 5.4.2.

6.1 Case study application and user feedback

Case study application of the methodology was an important element of its design, focusing on user feedback from energy engineers. The involvement of later users is novel in developing a methodology for SPH-system integration and was a neglected aspect in previous research, as discussed in the literature review (chapter 2).

The choice of energy engineers as methodology users was considered from the very beginning, starting with development of the methodology structure (section

4.2). It was assumed that energy engineers would typically have a high level of knowledge regarding energetic analysis (the first methodological element). The level of knowledge was assumed to decrease with each further element. The expertise of energy engineers is generally sufficient to carry out analysis of the first element of the methodology, but must be complemented with specific knowledge from expert design engineers for subsequent elements. Case study application confirmed the decreasing level of knowledge of energy engineers with each consecutive methodological element. Furthermore, case study application reflected different levels of knowledge of different energy engineers regarding energy issues.

An example of these different knowledge levels can be seen in the definition of the two case studies. These represent two categories of energy engineers in terms of level of energy knowledge. The energy engineer within a large enterprise is typically a full-time energy engineer (FTEE) and differs from the energy engineer of a small or medium-sized enterprise, who is typically part-time (PTEE). It was assumed that the knowledge level of the FTEE would be higher than that of the PTEE. Application of the methodology confirmed these differences in knowledge with evaluation of the case studies. It was hence important, not only to involve different users in development of the methodology, but also to make distinctions on the basis of their level of background knowledge. This helps define the level of individual support that needs to be provided by design engineers, which is always required. Independent application by energy engineers is not supported by the methodology.

Tools and measures that are already in use within companies can be adopted and implemented within the methodology. This increases its usability. However, the availability of such tools and measures is limited. To ensure results of sufficient quality, the proposed methodology requires additional tools and measures that are generally beyond the knowledge of energy engineers (e.g., pinch method or simulation). The addition of extra tools and measures results in reduced usability but is regarded as an acceptable trade-off.

The evaluation of overall usability is therefore an important aspect. Results show that energy engineers’ knowledge is sufficient for energetic analysis and is generally sufficient for energetic optimisation required within their daily work. Usability decreases strongly for solar process heat and simulation methodological elements. Design (e.g. solar process heat system) and tool expertise (simulation) is not commonly available. Support from specific design engineers is hence required, limiting individual usability by energy engineers.

Usability is also influenced by the definition of essential functions (section 5.4.1). As explained in section 5.4.1, for application of an essential function, energy engineers require detailed instructions and support by design engineers. Function assessment (section 5.4) shows that essential functions relate mainly to ‘solar process heat system’ and ‘simulation’ elements. This assessment distinguishes between two parts of the methodology. The elements ‘energetic analysis’ and ‘energetic optimisation’ comprise the first part of the methodology, with higher usability and less essential functions than the second part. Many energy engineers can carry out these functions using their existing knowledge, meeting usability expectations. The elements ‘solar process heat system’ and ‘simulation’ comprise the second part, with lower usability. Both elements include mainly essential functions. This makes it necessary to utilise expertise from system designers to support energy engineers.

Prior knowledge regarding energy issues was found to vary; this should be taken into account for flexible methodological application. The evaluation of flexibility (section 5.4.2) showed that each of the elements could be utilised independently, as could the various functions. The methodology therefore has the required level of flexibility.

This approach to methodological design has been shown to be very promising, enabling step by step development for the intended user, by moving from a methodological draft through to case study application, and finally to assessment based on user feedback.

6.2 Comparison of methodologies

The author's methodology for design of a solar process heat system and its integration with existing systems for supply of low-grade industrial heat has been found to fulfil requirements that are unmet by existing guidelines.

The comparison of the author's methodology with existing SPH-guidelines in section 5.5.2 confirmed improvements. New functions, such as 'heat source management' or 'simulation', complete the insufficient and missing features of existing SPH-guidelines. Application of the methodology showed an adequate level of detail for features that were insufficiently developed in existing SPH-guidelines (such as 'energy balance' or 'concept development').

A higher level of detail increases the effort required to apply the developed methodology, which might be perceived as a disadvantage for the user. However, the defined level of detail leads to comprehensive findings for technical and economic evaluation. This aids in decision-making.

The developed methodology provides a complete and very detailed procedure, from energetic analysis to an evaluated system concept ready for implementation. However, the higher level of detail and the integration of new tools and measures (e.g. pinch analysis) limit independent application by energy engineers. This illustrates an important difference between existing SPH-guidelines and the developed methodology. The existing SPH-guidelines present general facts and recommendations for integration of solar process heat with industrial heat supply. They are intended primarily to inform interested audiences. In contrast, the developed methodology guides energy engineers, supported by design engineers, towards this objective, through a detailed step-by-step process, aided by selected tools and measures.

6.3 Contribution to scientific knowledge

The following section describes the contribution to scientific knowledge represented by this research:

The research provides a novel methodology for design of integrated SPH systems for industry. As the analysis of SPH-guidelines in section 2.6.2 demonstrates, this is not a completely new approach. Development of the methodology, however, complements existing tools that have been shown to be insufficiently developed, by adding missing features. This results in a clear and complete structure that supports efficient integration of solar process heat within low-grade heat supply systems. With its focus on the heat supply system, the methodology is also independent from a specific industrial sector. The design process for the methodology combines development of its structure with an understanding of the requirements of its audience.

This process of the methodology design is novel. It is intended to facilitate development of a tailored methodology for purposeful application. The case study application is not only a test bed for the developed methodology but a means of collecting feedback on its usability. This enables evaluation of essential functions (section 5.4) and reflection on necessary tools and measures, as well as on the appropriate level of detail from a user point of few.

The contribution of the design process to scientific knowledge can be separated into three parts:

1. From the very beginning, the methodology design process considers the level of expertise (Figure 4.5 in section 4.5) of the audience (energy and design engineers). Early-stage implementation ensures the provision of functions that complement the present level of background knowledge of the audience. The result is a methodology that supports and complements the experience of energy and design engineers, while filling gaps in their knowledge.
2. The case study application gave the audience the possibility to work with the methodology. This helped improve the methodology's usability (chapter 5).
3. The feedback of energy engineers from within case study companies completed the design process and enabled comprehensive usability evaluation of the whole methodology, including of its functions and related

tools and measures. Further, this enabled definition of essential functions (section 5.4.1) and related energy requirements.

As described, the audience plays an important role within the design process of the methodology. Further improvement of usability and evaluation of essential functions (section 5.4.1) will contribute to its widespread use.

6.4 Recommendations and further investigation

The research contributes to scientific knowledge by developing a novel methodology using a novel methodological design process. The findings allow the researcher to obtain answers to identified research questions.

However, further application of the methodology to more than two case studies would allow investigation of the transferability and flexibility of methodological functions, for different industries and companies of different sizes. The results would additionally help to evaluate possible or necessary modifications to the methodology, relating to the following aspects:

- First, it is recommended to have further case studies for other industries. Breweries and dairies represent a broad range within the food industry and were chosen because of promising conditions for solar process heat in connection with low-grade heat supply. As analysed within the literature review, other industries differ with respect to heat supply systems and production. This affects heat supply temperature levels and temporary demand for heat. Application of the methodology should be analysed in this context, with a focus on low-grade heat.
- Second, it would be recommended to have case studies with companies of different sizes. The researched case studies comprised a small and medium-sized enterprise (brewery) and a large enterprise (dairy). It is necessary to extend the findings, to at least a large brewery and a small or medium-sized dairy. This would enable a more detailed comparison of both food industry sectors.

- Third, it would be recommended to analyse dependence on specific knowledge of energy engineers. The case studies indicate differences in this regard; it is assumed that these were related to company size, but this needs to be confirmed.

Independent application of the methodology by energy engineers was not shown not to be possible during this research. Definition of the minimum required level of knowledge among engineers should therefore be investigated. This could promote adoption of the methodology by further matching it to user requirements.

One finding of the case study was that application of the methodology enhanced the level of knowledge of energy engineers. Based on this finding, a training program for methodological application could be developed. This could be used to explore whether training can lead to application of the methodology without support or instructions by design engineers, but can also indicate the degree of training required.

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Appendix A Methodology background

A.1 Process heat

Steam is the most common heat transfer medium in the food industry and used for direct and indirect heat applications. Essential advantageous of steam are a high heat capacity and transmission power. Regarding food industry, it is also important that it is non-toxic. Steam is mainly used as saturated steam at operating temperatures between 100°C and 220°C (Hardy, 2009). Depending on the supplied processes, an alternative option is high-pressure water at a temperature up to 170°C or just hot water at a temperature below 100°C (Kunze, 2010). This is possible as companies optimise (reduce) process temperatures and use new process technologies. Using hot water as heat transfer medium enables the integration of low-temperature energy sources as solar process heat or waste heat.

This Fossil fired steam boilers are a main component of the steam system as illustrated in Figure A.1.

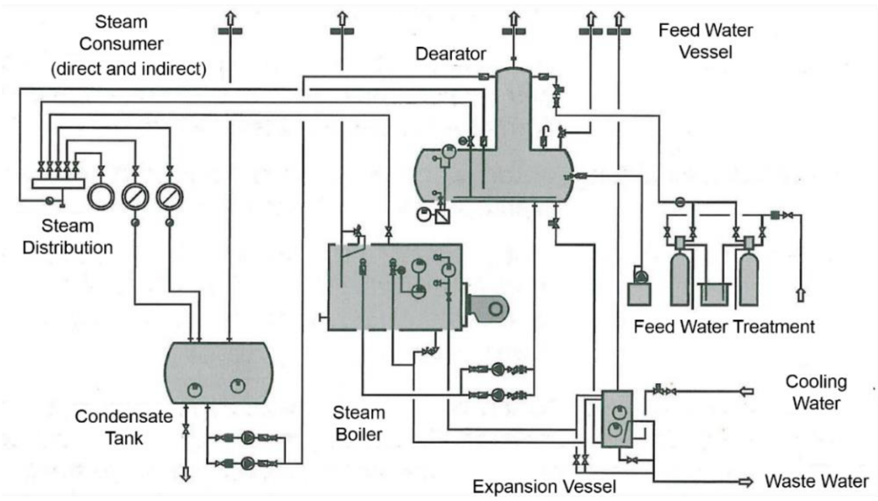


Figure A.1: Components of a process steam system (cf. Hardy, 2009)

The classification of steam boiler is with available power and steam output. Additionally, Kunze (2010) distinguishes

- Fire-tube exhaust gas-tube boilers;
- Water tube boilers; and
- High-speed steam producers.

State-of-the-art steam boilers are available in a wide range of power categories. It starts from less than 100 kW_{th}, or a steam supply below 100 kg h^{-1} at a low pressure of 0.5 bar and 100°C and reaches more than 38,000 kW_{th}, or a steam supply of 55,000 kg h^{-1} at a pressure of 30 bar and a temperature level of 300°C. Depending upon the configuration, nearly every application in breweries and dairies can be served with a boiler system. Figure A.2 and Figure A.3 show typical steam boilers for small and medium-sized companies. These boilers can supply saturated and superheated steam in a range from 175–28,000 kg h^{-1}.

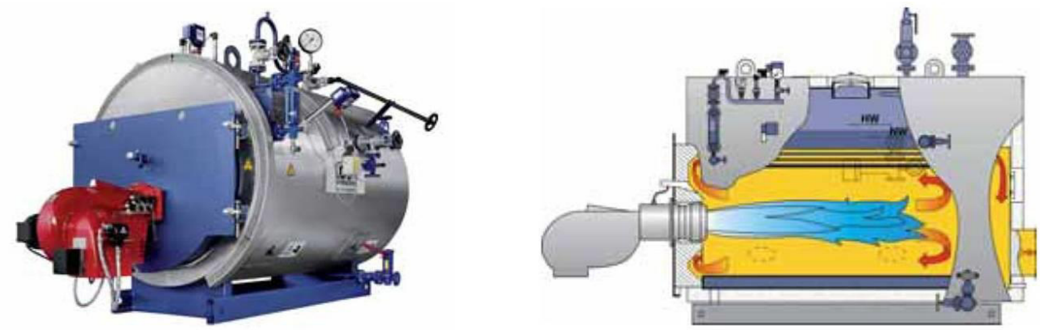


Figure A.2: Compact steam boiler for low to medium steam demand (Loos, 2012)

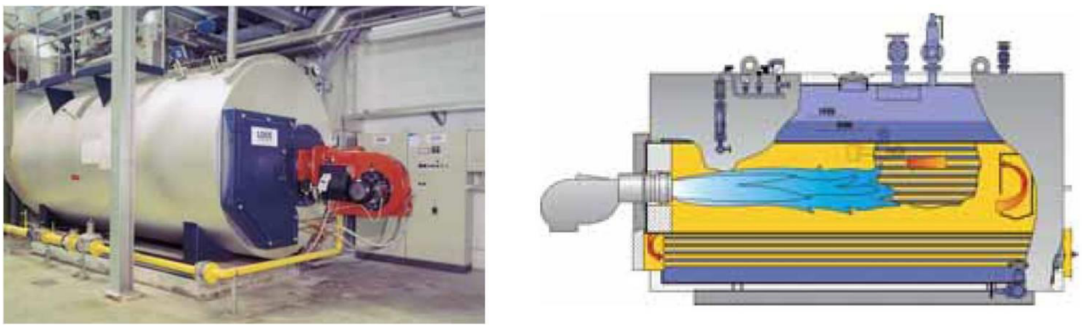


Figure A.3: Universal steam boiler for saturated and superheated steam (Loos, 2012)

Additionally, the high flexibility of power and steam supply provides major advantages for this kind of energy production. This is the reason for steam boilers as the central process heat source in the food industry.

A.2 Cooling and cooling systems

The food industry needs cooling energy for production processes and space cooling. Two different distribution systems can be distinguished at breweries and dairies. Direct evaporation of a refrigerant (direct cooling) is often applied for space cooling but also for process cooling. The refrigerant evaporates in direct contact to the medium that has to be cooled. Using a cooling agent for the transfer of cooling energy to the application is the second option. This are often ice water systems (Figure A.4) where an evaporating coil is installed in a large water tank. A layer of ice grows at the evaporator coil and supplies ice water at nearly 0.5°C to the consumer (Kunze, 2012). The ice water tank acts as a cooling storage and allows running smaller chillers independent from cooling requirement. In contrast, more energy for pumps is necessary in fact of the additional ice water cooling circuit and also the energy loss of the ice water tank must be compensated.

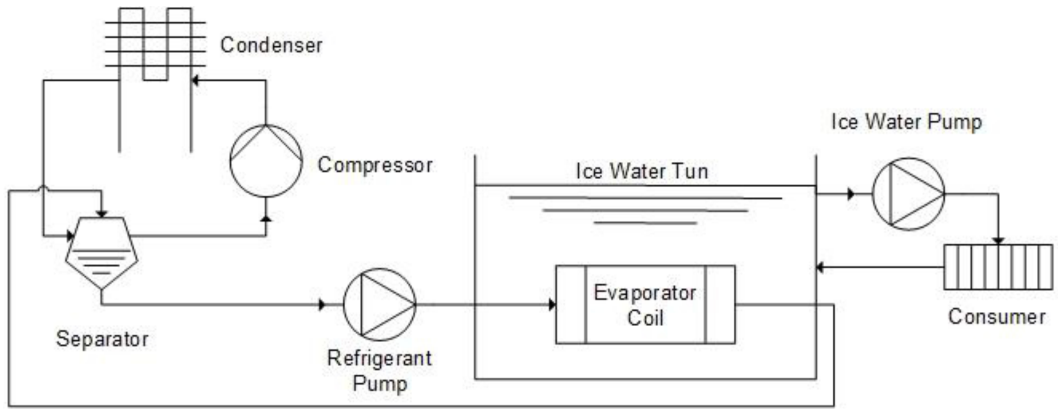


Figure A.4: Ice water cooling schematic

Compression chillers are the main part of the system and the compressor component is the largest energy consumer. Two compressor types are market available:

- Piston compressor (Figure A.5), where pistons compress the refrigerant.
- Screw compressor, which works with two helical rotors in a closed housing where the refrigerant is compressed.

The cooling power depends on the compressor type and on the system configuration. The available compressors on the market cover a range of cooling power from about 50 kW_{th} up to more than 2,000 kW_{th} for single chillers, as shown in Figure A.5. By using a combination of several different compression chillers, almost any performance category can be configured in cooling systems.

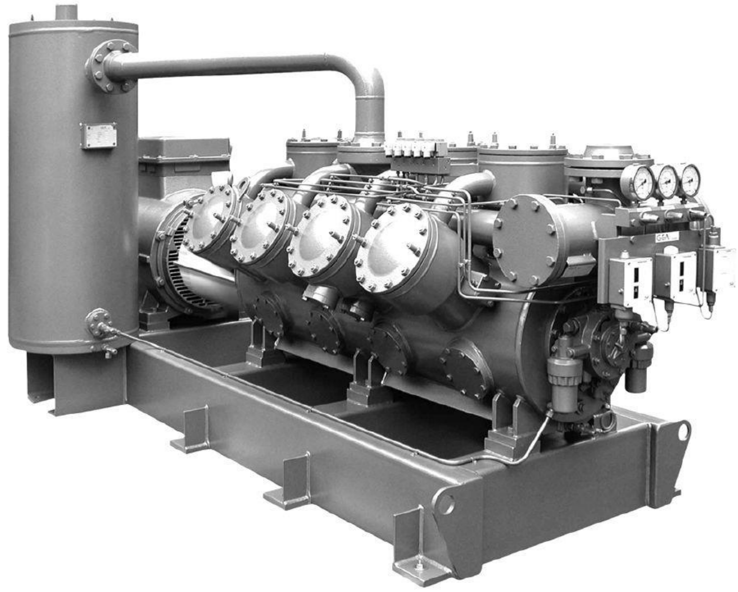


Figure A.5: Piston compressor Grasso 1212E (GEA, 2012)

Compression chillers can be driven with different refrigerants. In both breweries and dairies, the most common refrigerant is ammonia (NH_3). Additionally, R12 (dichlorodifluoromethane) and R22 (chlorodifluoromethane) are well known and commonly used. Each of these refrigerants has disadvantages. For example, NH_3 is toxic and explosive, while R12 depletes the stratospheric ozone layer.

To provide cooling power, huge amounts of electricity are necessary for driving the compressors. In addition, equipment must be available for cooling the compressors. The waste heat generated during cooling offers the possibility of heat recovery. This topic will be considered as part of the optimisation and improvement of energy efficiency.

A.3 Compressed air systems

Besides process heat and cooling, compressed air is an important useful energy in dairies and breweries. Depending on the company structure and product portfolio about 8% of the electricity at dairies and 6% of the electricity at breweries is used for compressed air (Energieagentur.NRW, 2012). Piston or screw compressors are mainly implemented as single engines or plants. It is required for various applications, e.g. (Kunze, 2010; Wieting, 2009):

- as tensing or rinsing gas
- aerate of products
- pumping raw materials and products
- pneumatic applications
- filling of bottles and glasses

Compressed air is on the one side a very useful energy for the food industry. It is simple to keep compressed air clean and use it in direct contact with food. However, on the other side this form of energy is very inefficient. The working fluid contains only 4% to 5% of the consumed electricity (Bierbaum, 2004). About 95% get lost as waste heat from air and motor cooling. For running an efficient compressed air supply, waste heat recovery is essential. Large amounts of the energy can be recovered as low-temperature heat.

Besides waste heat recovery from compression chillers, this will also be considered within the optimisation of the energy supply of breweries and dairies.

A.4 Pinch analysis

Bodo Linnhoff developed the pinch analysis in the 1970s for the optimisation of energy demand in oil refineries and the chemical industry (Kemp, 2007). In a simplified form the methodology behind is the energetic comparison of 'hot' and 'cold' streams. The result is a definition of direct heat energy exchange between the streams as well as cooling and heat requirement. Finally, the development of heat exchanger networks is able with the information of the analysis. The pinch analysis can be separated in the following activates:

- Acquisition of <u>input data</u> for the streams (processes)
- Determination of the pinch and calculation of the <u>composite curves</u>
- Development of the <u>grand composite curve</u>

- Development of the heat exchanger network

The parameters of the streams provide the input data. A hot stream on the one side needs cooling energy and a cold stream on the other side needs process heat. This offers the possibility of a direct heat exchange between the streams. Figure A.6 illustrates exemplary four independent cold and hot streams with the process temperatures T_{in} and T_{out}.

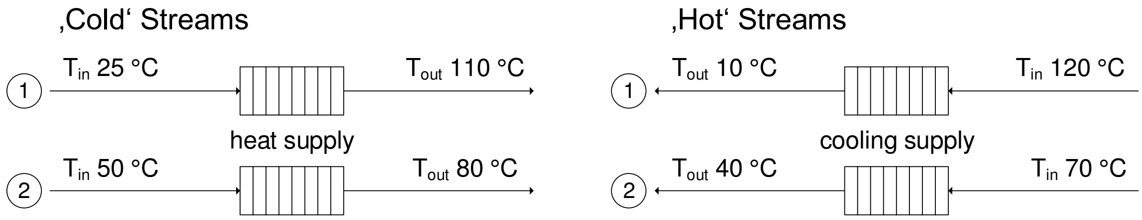


Figure A.6: Exemplary hot and cold streams

Table A.1 gives the remaining process data for the exemplary streams. Besides heat rate H, mass flowrate $\dot{m}$ and specific heat capacity c_p, the heat capacity flow rate CP is an important figure for the pinch analysis. A stream is defined by the heat capacity flowrate CP (equation (A.1)) and its heat rate H (equation (A.2)).

$$CP = \dot{m} \times c_p \qquad (A.1)$$

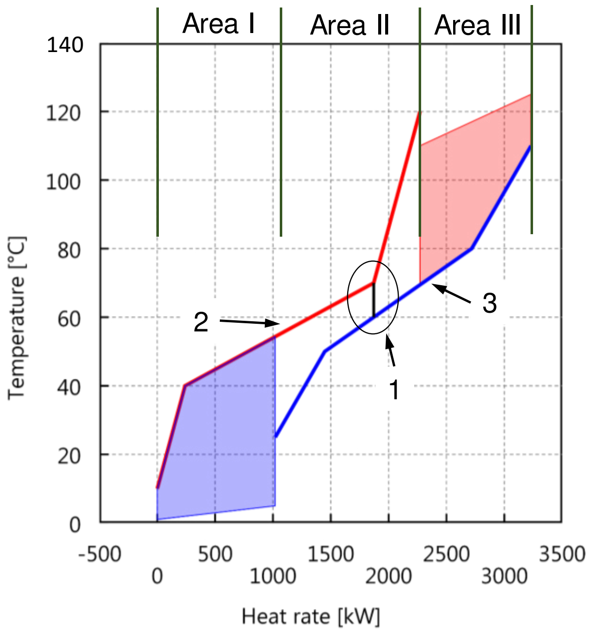
$$\Delta H = CP \times (T_{in} - T_{out}) \qquad (A.2)$$

Table A.1: Process data 4-stream example

	Mass flowrate $\dot{m}$ [kg s^{-1}]	Specific heat capacity c_p [kJ kgK^{-1}]	Heat capacity flowrate CP [kW K^{-1}]	Heat rate H [kW]
Cold Stream 1	4.5	3.8	17.1	323
Cold Stream 2	6	4.21	25.26	126.2
Hot Stream 1	2	4	8	-440
Hot Stream 2	11	4.21	46.31	-126.4

Figure A.7 shows a graphical plot steam analysis in the temperature / heat rate diagram. The cold and hot composite curves are the addition of the cold streams and hot streams (

Table A.1). Both curves initial start at a heat rate H = 0 and show the individual heating and cooling. The cold composite curve then is shifted along the heat rate axis to the pinch, what is the defined ΔT_{min} between the curves.



I	cooling requirement
II	heat recovery
III	heating requirement
1	Pinch
2	Hot Composite Curve
3	Cold Composite Curve

Figure A.7: Composite curves 4-stream example

The pinch is of specific importance. It limits with ΔT_{min} the heat recovery potential and defines external heat and cooling requirement. The pinch affects also the heat exchanger configuration of the later heat exchanger network (HEN). The lower ΔT_{min} of the pinch is the larger is the necessary heat exchanger area. This aspect influences further the overall economy of the HEN. Kemp (2007) described three rules how to handle the pinch for a maximum energy efficiency:

- No heat transfer across the pinch
- No external cooling above the pinch
- No external heating below the pinch

Along the heat rate axes, three areas are distinguished (Figure A.7). Cooling and heating requirement are areas with external energy supply. Heat recovery between the curves is only feasible at the overlapping area. The heat rate a maximum for each area and objective regarding energy efficiency.

The grand composite curve (Figure A.8) represents the net heat rate at each temperature level. Therefore, the hot composite curve is shifted along the temperature axis with -½ ΔT_{min} and the cold composite curve with +½ ΔT_{min} as the curves touch at the pinch. The heat capacity flow rate CP varies between the intervals (Figure A.8) and is here defined with equation (A.3).

$$\sum CP_{Hot} - \sum CP_{Cold} \qquad \text{(A.3)}$$

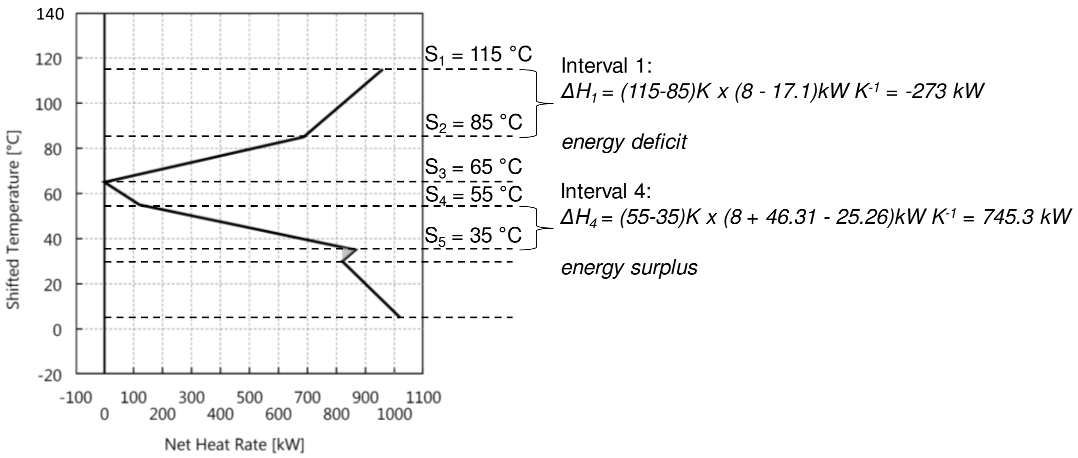


Figure A.8: Grand composite curve 4-stream example

ΔH_i represents the net heat rate (equation (A.4)) of the interval and is also for the identification of an energy surplus or deficit. This is exemplary illustrated in Figure A.8 for interval 1 with an energy deficit of 273 kW_{th} and for interval 4 with an energy surplus of 745.3 kW_{th}. With a surplus, it is possible to transfer energy to the interval below. External energy supply is necessary to compensate a deficit.

$$\Delta H_i = (S_i - S_{i+1}) \times (\sum CP_{Hot} - \sum CP_{Cold}) \qquad \text{(A.4)}$$

Result is finally the heat exchanger network (Figure A.9). The HEN of the 4-stream example illustrates heat recovery between the streams and remaining energy demands. ‘Hot Stream 1’ for example supplies on the one side 400 kW_{th} to ‘Cold Stream 2’ and increases the temperature from 60°C to 75.8°C. The cold streams on the other side supply both cooling energy to the hot streams. The figure shows also the remaining energy demand (cooling for hot stream and process heat for cold stream) for each stream and additional the external heating and cooling requirement is evident from the HEN.

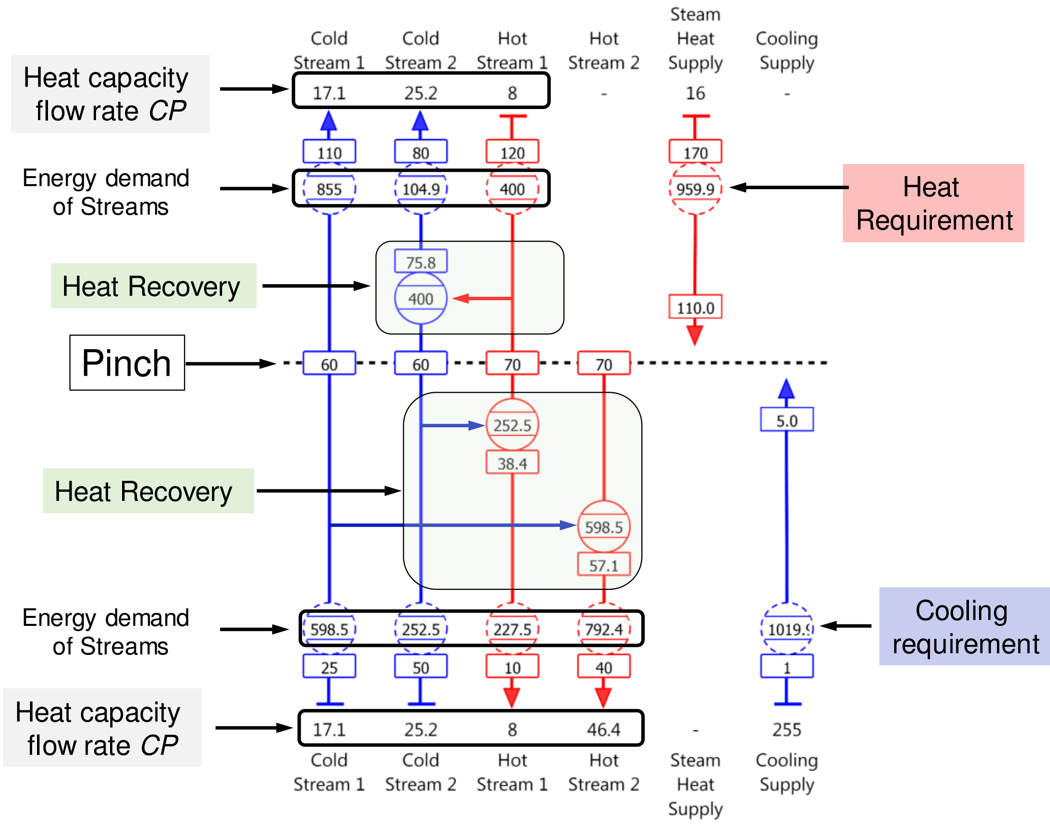


Figure A.9: Heat exchanger network 4-stream example

The originally development of the pinch analysis was for continuous processes (Kemp, 2007) as the four stream example shows. As defined, these continuous processes run parallel and do not change heat flow rate. Heat recovery between the streams is simple feasible. However, the final HEN does not consider the structural conditions and spatial division of the streams and requires an additional analysis.

In the food industry, and especially in breweries and dairies dominate batch processes. The application of the pinch analysis to batch processing requires some modifications as Kemp (2007) described. Krummenacher (2002) modified previous and developed new approaches to handle batch processes and the various challenges with pinch analysis.

Figure A.10 describes an example of two sequential batches with each one hot and cold batch with the time slice model (TSM) (Kemp, 2007). Cold batch 1 is running from t_{start} = 0 to t_{stop} = 0.3 with a constant heat rate of 20 kW_{th} heating requirement and hot batch 1 is running from t_{start} = 0.4 h to t_{stop} = 0.8 h with a constant heat rate of 30 kW_{th} cooling requirement. The same applies for batch 2 that starts at t_{start} 1.0 h. It illustrates clearly the problem of batch interval and direct heat recovery. It is not able to exchange energy between the batches without adaptions.

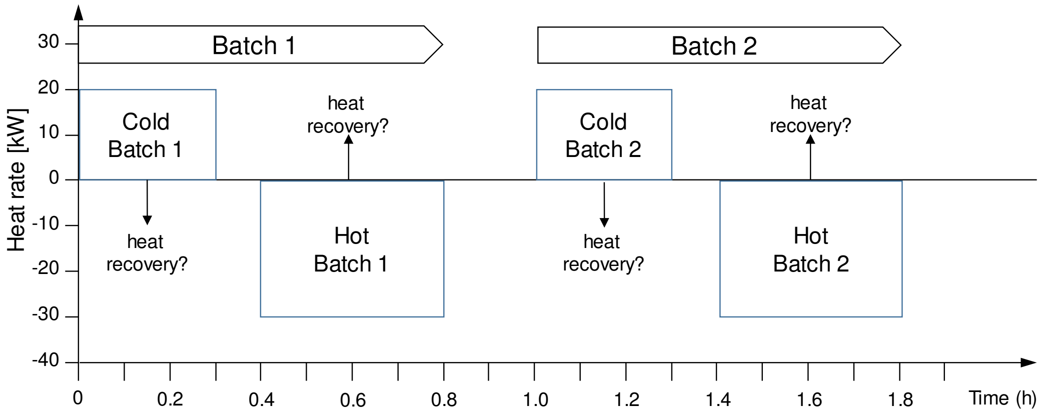


Figure A.10: Example for batch processing

One approach to enable direct heat recovery with batch processes is rescheduling of the production flow. However, this limited regarding technical and energetic aspects (cf. Kemp, 2007):

- Individual duration and different heat rates lead to different loads
- The process is in a vessel an not flowing throw a heat exchanger
- Same equipment for heating and cooling

Figure A.11 illustrates the rescheduling for batch 2 of the example. The hot batch 2 starts now at the same time like cold batch 2. A direct heat recovery is possible but limited to 6 kWh_{th} because of different loads. Hence, always 6 kWh_{th} of external cooling is necessary.

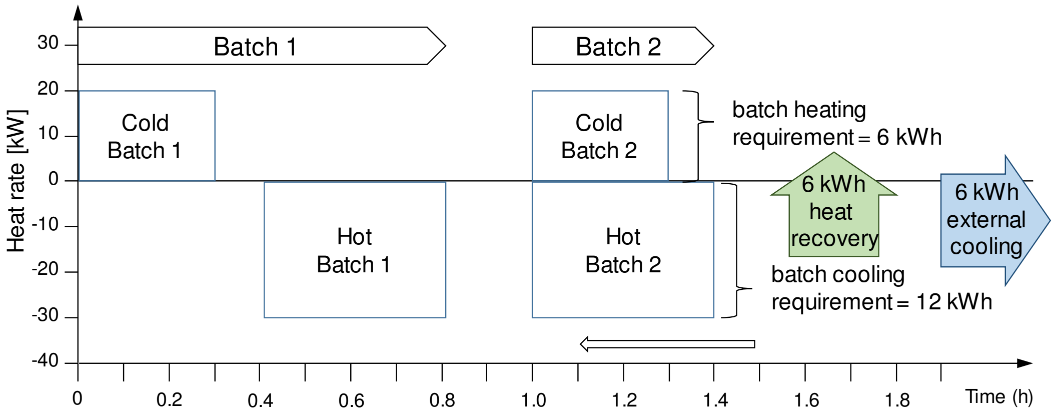


Figure A.11: Rescheduled batch processing

Rescheduling however, stands for a change of production sequence and means comprehensive interventions in operation processes. This requires not only its essential possibility but also the readiness of the company.

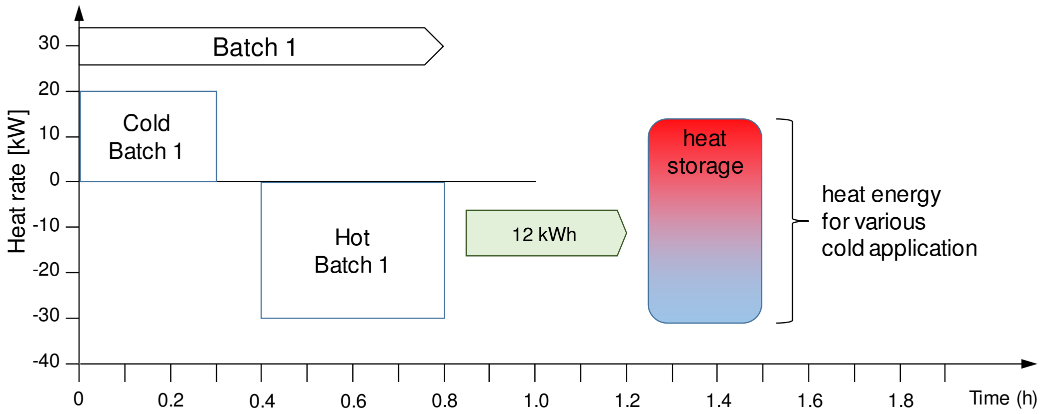


Figure A.12: Batch processes with heat storage integration

A second approach is an indirect heat exchange with the integration of heat storages. In contrast to the approach before, the production flow is not primary in focus and the process sequences remain (Figure A.12). The heat energy of hot batch 1 is pre-stored and available for later applications.

Heat storages provide the possibility of indirect process heat recovery with batch processes. However, in comparison to direct heat exchange the storage causes additional energy losses. A consideration of the losses is required and must be included in an energy balance of the system. Figure A.13 shows a heat recovery circuit (*HRC*) with heat recovery from hot batches, heat supply to the cold batches and the heat storage with energy losses.

- Q_{hb} heat recovery from hot batch to heat storage
- Q_{cb} energy supply to cold batch from heat storage
- Q_{loss} energy losses of the heat storage

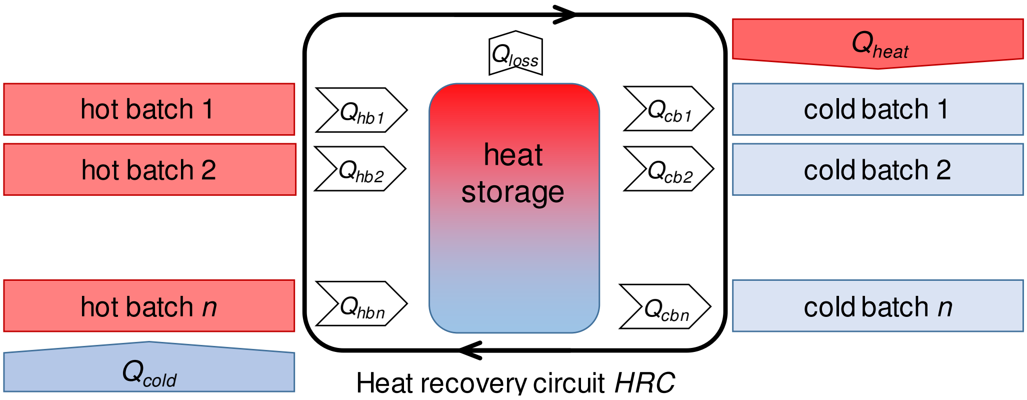


Figure A.13: Heat recovery circuit *HRC*

This HRC is basis for an energy balance to define the energy losses of the heat storage as well its significance on total heat recovery. Equation (A.5) is for the heat recovery potential HR_{pot}.

$$HR_{pot} = \sum Q_{hb} - \sum Q_{cb} - Q_{loss} \tag{A.5}$$

Indirect heat recovery is advantageous with batch processing. However, a combination with rescheduling would provide additional heat recovery opportunities.

A.5 Solar process heat systems

Flat plate collectors are the standard in Germany and Europe and have a market share of 90% (DSTTP, 2014). Vacuum tube collectors provide the advantage of higher operation temperature and a better efficiency at a temperature above 80°C (Bollin, 2014) but with much higher costs (cf. Solaratlas, 2013). With the approach of low system costs, flat plate collectors are preferred.

Short-term heat storage (capacity < 2 days) compensates time related differences in the availability of solar energy and the energy demand. This aims to enhance the reliability of the SPH-system. The volume depends on collector area and duration of storage. A guide value for the volume is in connection with the system efficiency 50–80 l $m^{-2}{}_{ca}$ (Bollin, 2013). Larger volumes do not enhance the system efficiency remarkable (Figure A.14). An exact volume determination is just possible with a simulation.

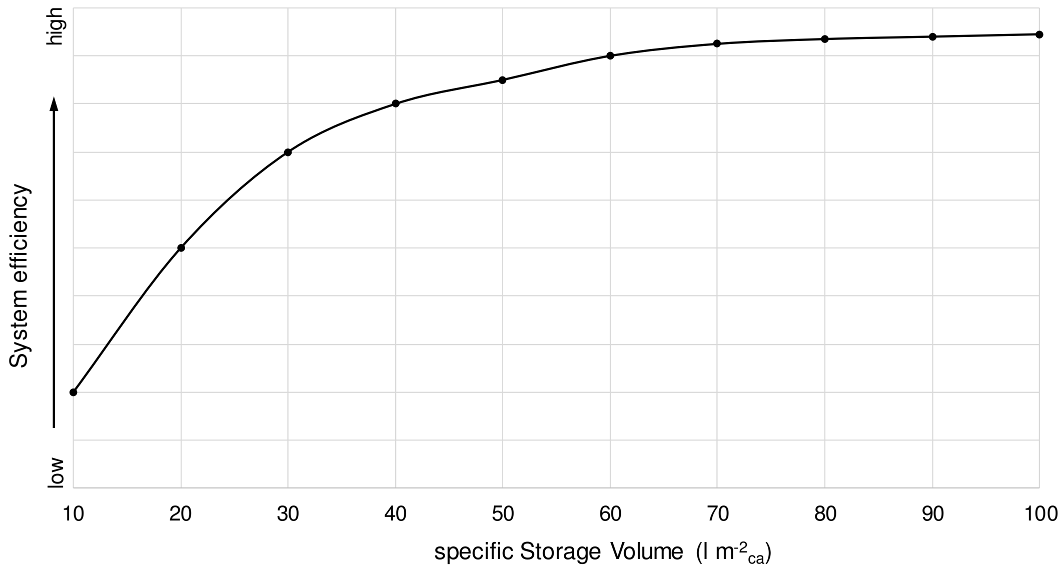


Figure A.14: Specific storage volume (cf. Bollin, 2013)

Dincer (2012) described three processes for a thermal storage system (Figure A.15). Besides storing, this is charging and discharging. These must ensure a maximum load capacity, the lowest return temperature to the collector array and the highest useful temperature from the storage to the energy consumer.

Charging and discharging of heat storages is possible with several configurations (Figure A.16). A pipe connection to the top and bottom of the storage is the simplest configuration. Large volume flows in the storage charging circuit, can cause an unfavourable stratification of the storage medium and decrease the usability storage capacity. However, this effect lowers with large storage volumes.

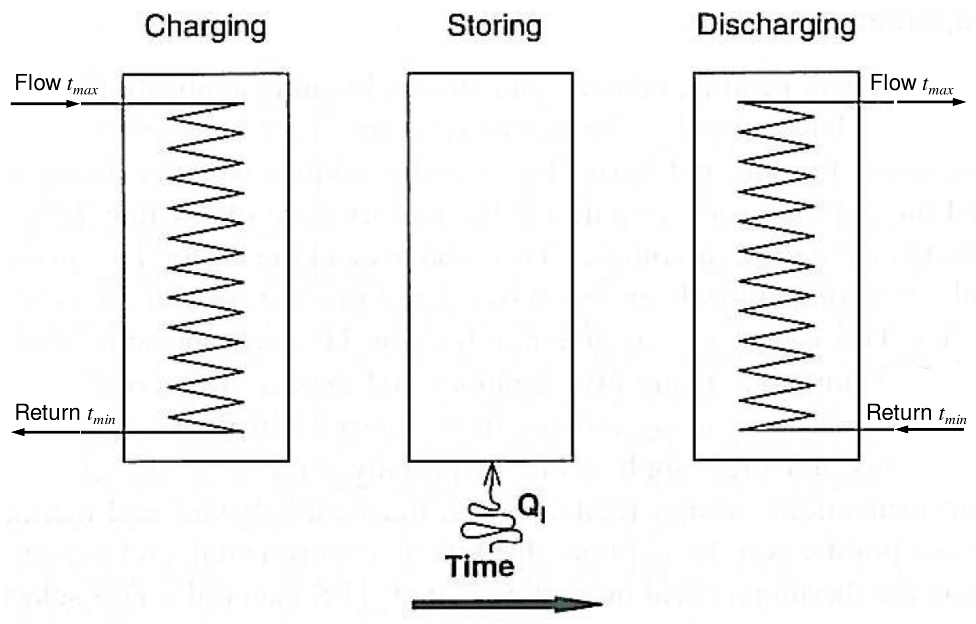


Figure A.15: Storage processes (cf. Dincer, 2012)

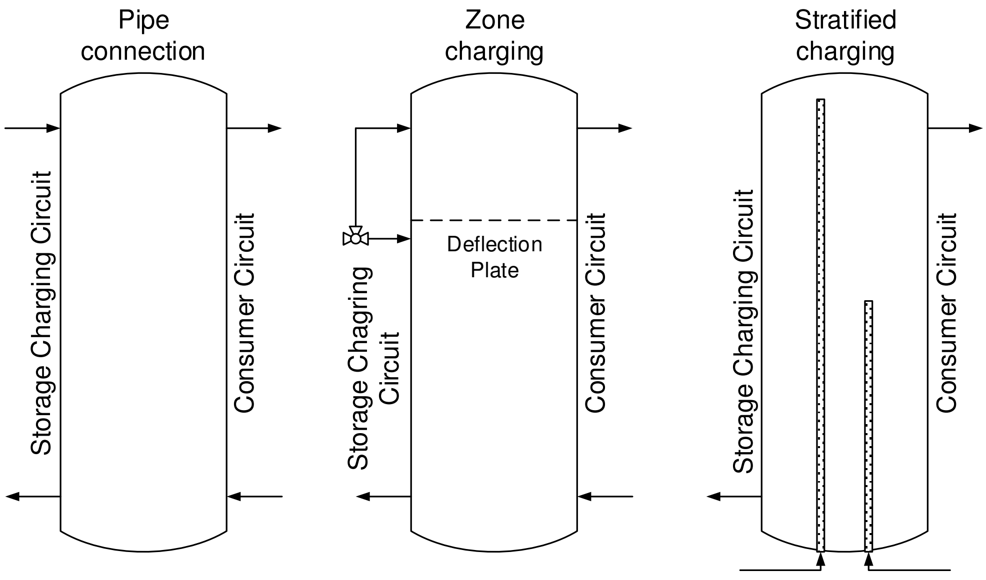


Figure A.16: Charging and discharging configurations

The zone charging configuration works with two or more charging levels. A deflector plate can additionally prevent a mixing of the storage medium and keeps the defined temperature level more steady. This configuration needs a tailored charging control strategy, a hydraulic with three-way-valves and additional storage connections. Stratified charging uses the density difference of the storage medium at different temperature levels. A specific charging pipe in the storage stratifies the storage medium. This lead to an optimised distribution of temperature. Discharging for all configurations is at the top position of the storage and supplies the consumer circuit with the maximum storage temperature.

The System hydraulic focus here on the connection of collectors. Serial and parallel strings are the basis configurations. Favourable for the design of large collector areas is with Schnauss (2011) a combination of both. This parallel connection of serial strings (Figure A.17) is also common in several demonstration plants (Solarthermie2000, 2013). The collector connection aims to keep the pressures drop of the collector array low and to avoid unnecessary piping.

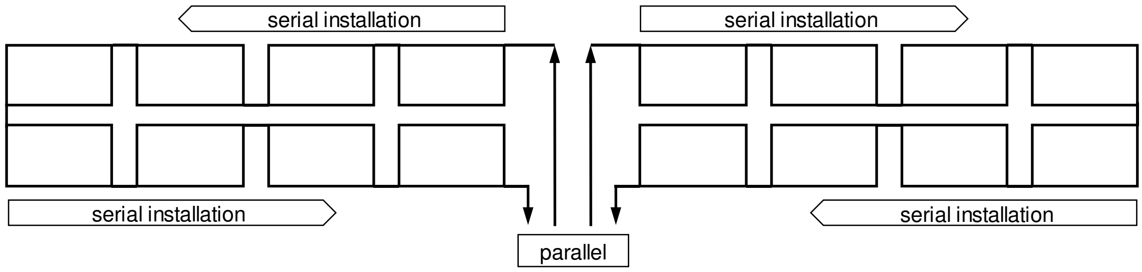


Figure A.17: Collector connection – combination of serial and parallel strings

The volume flow rate affects the collector hydraulic concerning pipe diameter and pressure drop. However, even more important is the temperature difference between collector inlet and outlet. The VDI (2014) describes a low-flow-concept and a high-flow-concept (Table A.2). However, the volume flow rate is not a fixed value. Kaltschmitt (2013) designates 10–15 l h^{-1} m_{ca}^{-2} for low-flow and 15–50 l $h^{-1} m_{ca}^{-2}$ for high flow.

On the one side, the flow concept aims to supply high specific collector earnings at high temperature from the collector area to the storage. High temperatures should further be available as soon as possible afterwards system start. On the other side, the flow concept should enable a simple hydraulic of the collector array and cost efficiency. This favours in most applications the low-flow-concept with a system adopted volume flow rate.

Table A.2: Low-flow and high-flow-concept*

		Low-flow	High-flow
Volume Flow Rate Medium: Water-Glycol-Mixture *Collector Circuit*	$l\ h^{-1}\ m_{ca}^{-2}$	10–25	25–40
Volume Flow Rate Medium: Water *Storage Charching Circuit*	$l\ h^{-1}\ m_{ca}^{-2}$	9-23	23-37
Temperature Difference (collector inlet → outlet)	ΔK	high	low
Pipe Diameter	-	small	large
Pressure Drop	Δp_{ca}	low	high
Pump Power	W	low	high

*(cf. VDI, 2014)

Solar-thermal systems located in central and northern Europe need frost protection. Therefore, a water-glycol-mixture is mainly used. Additional property of these fluids is protection against corrosion. Disadvantageous is a lower thermal capacity and conductivity or a higher viscosity. For that reason, a few system concepts with water as heat transfer medium are available. Frost protection in this case needs a complex control strategy and heat energy transfer from the storage or an auxiliary heating to the collectors. Therefore, the concept development considers only water-glycol-mixture.

Function of the control strategy is to provide as much useful energy from the solar-thermal system as possible. The system control gets therefore data from sensors and gives signals to the pumps. Switching on and off the pumps means for the simplest case a comparison of the collector temperature T_{col} and storage temperature $T_{st,low}$. Long piping from the collector array to the storage require additionally bypass functions to avoid storing ‘cold’ energy at system start. This is able with a comparison of the bypass temperature T_{byp} and the storage temperature $T_{st,low}$. Additional defined hysteresis for all switching states prevent also transferring ‘cold’ energy and frequent switching of the pumps. Figure A.18 gives an example for this control strategy with solar circuit and storage charging circuit as well as bypass control.

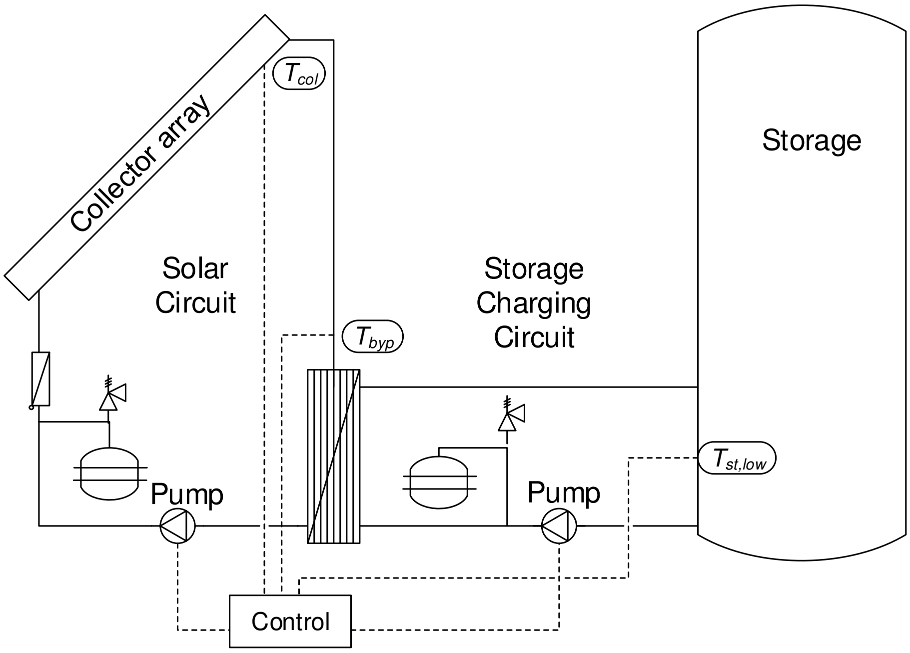


Figure A.18: Example SPH-system with solar and storage charging circuit

Design and implementation of SPH-systems to the low-temperature heat considering structural conditions of a company are significant aspects. This chapter will analyse and evaluate different system variations. Main objectives are the simplicity of system and implementation but also an efficient and reliable service.

The defined system variations illustrated in Figure A.19, differ with solar process heat supply and storage charging. An essential distinction is here between direct and indirect heat supply. The feasibility of direct system requires energy consumption simultaneously with available solar process heat. A storage is therefore not necessary. Indirect systems consist of two circuits and storage. The use solar process heat is independent from the availability. Frost protection is each with a water-glycol mixture as heat transfer medium.

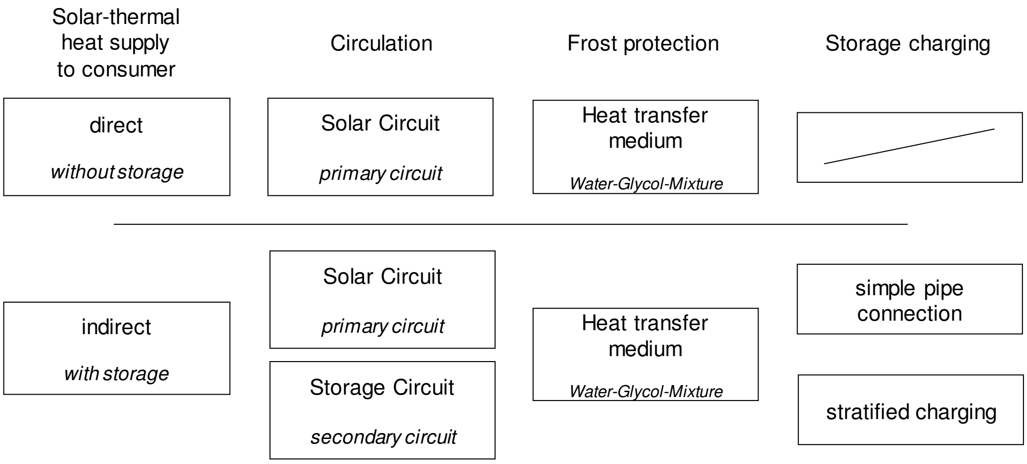


Figure A.19: Variations of SPH-systems

Direct process heat supply

Figure A.20 illustrates the configuration a SPH-system with direct process heat supply. The integration of solar energy is without storage only with a heat exchanger direct to the consumer.

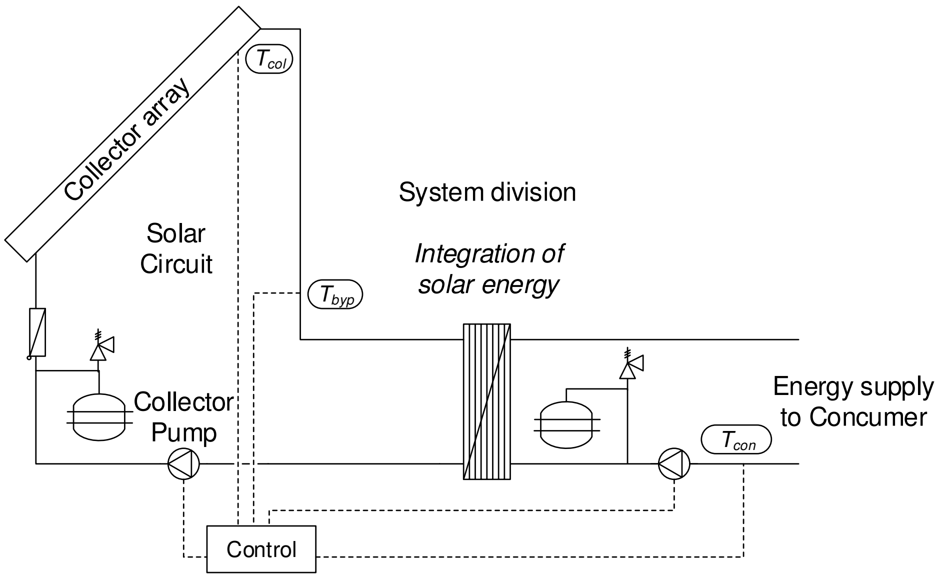


Figure A.20: SPH-system with direct heat supply

A water-glycol-mixture as heat transfer medium ensures frostproof in the solar circuit. The control compares first the collector temperature T_{col} with the consumer temperature T_{con} and then bypass temperature T_{byp} again with consumer temperature T_{con}. With defined hysteresis $T_{col} > T_{con}$ and $T_{byp} > T_{con}$ the circuits start operation and runs the collector pump. Advantageous is the simple and cost effective configuration. Disadvantageous is the necessity of direct use of available solar process heat to prevent stagnation. Hence, the energy consumption must be at least as large as the available solar process heat.

Indirect process heat supply

Figure A.21 shows an indirect heat supply configuration. Compared to the direct system, a heat exchanger separates the solar circuit in a collector circuit and a storage circuit. Heat transfer medium in the collector circuit is a water-glycol-mixture and responsible for frost protection.

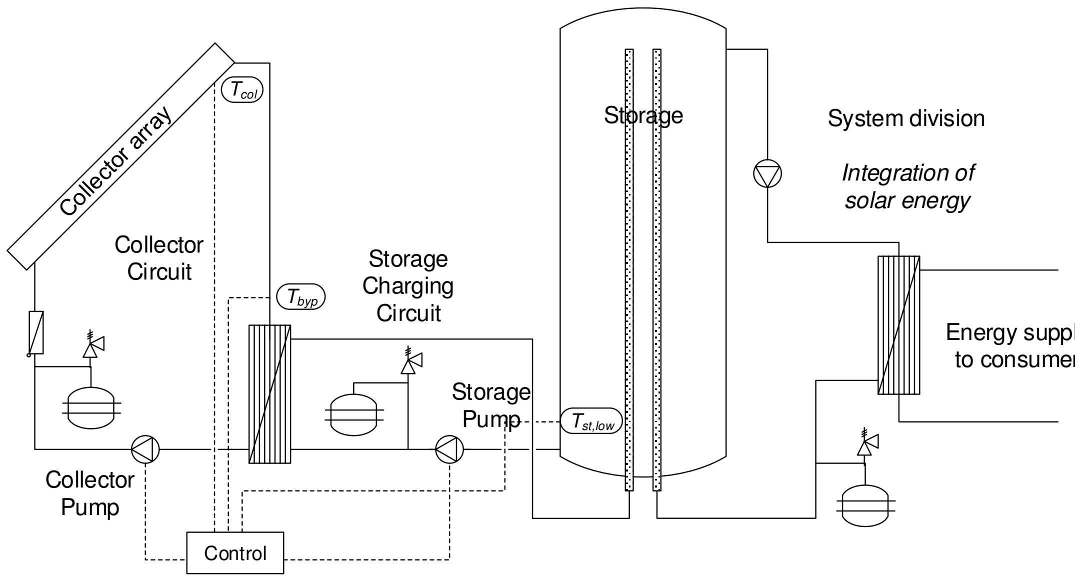


Figure A.21: SPH-system with stratified charging storage

The heat transfer medium in the storage circuit is water. As it is located inside, a frost protection is not required. The storage in this figure is illustrated with a stratified charging system. Another defined charging variation is a pipe connection. The control is similar to the direct system. Collector pump starts with a defined hysteresis $T_{col} > T_{st,low}$. Bypass in this system is the heat exchanger between the collector and storage charging circuit. The storage pump starts with a defined hysteresis $T_{byp} > T_{st,low.}$ All connections are to the lower part of the storage, what is a result of stratified charging. This kind of configuration is very promising for an integration in industrial LGH-systems:

- Independence of Solar process heat supply and energy consumption
- stratified charging for an optimised use of storage capacity
- frostproof with heat transfer medium
- appropriate for central Europe with temperatures below zero in winter

A.6 System simulation

The simulation aims to analyse the energetic behaviour of the system concepts. Focus is on heat sources and the energy supply to the consumers. The results from simulation enables an individual evaluation of each heat source but also a comparison among each other. Focus within the simulation is finally on the solar-thermal component of the system concepts and its efficient integration.

Objective of the simulation is to evaluate the conventional system models compared to energetic analysis of the systems in operation on the one side and to analyse the developed sustainable systems with the simulation results on the other side. Period for analysis and evaluation is regarding solar process heat a complete year beginning with the 1st January. A second object is the gradual optimisation of the sustainable system configurations. Focus of a subsequent sensitivity analysis is on the solar process heat to define finally optimised parameters for its economical evaluation.

Simulation environment is MATLAB/Simulink (The Mathworks, 2010). This is a standard tool for dynamic simulations used in industry and research. The extension CARNOT blockset (Hafner, 1999) is a toolbox based on Simulink. It provides validated model components for solar-thermal collectors, heat exchangers, storages or pumps. A ‘thermo hydraulic vector’ (THV) connects the model components and represents the fluid used for energy transport. The THV transmits all the fluid properties and is background for the calculation of thermodynamic changes of the fluid within the model components.

The system concepts consist all of energetic subsystems. Such a subsystem consists of different components and is applicable in several system concepts. Below is described the configuration of two example subsystems.

Process heat supply

The process heat supply is an essential subsystem for all system models. It represents a configuration with process heat source and process heat consumer. Figure A.22 shows the subsystem structure developed with MATLAB/Simulink and the CARNOT blockset (Hafner, 1999). An individual parameterisation of the blocks enables the adoption of this subsystem to several systems concepts. The heat exchanger is main component and completed with the process heat source and the process heat consumer. This subsystem configuration can be applied for different low-temperature energy sources — for example waste heat recovery from air compressors — and aims to provide defined process heat to a consumer.

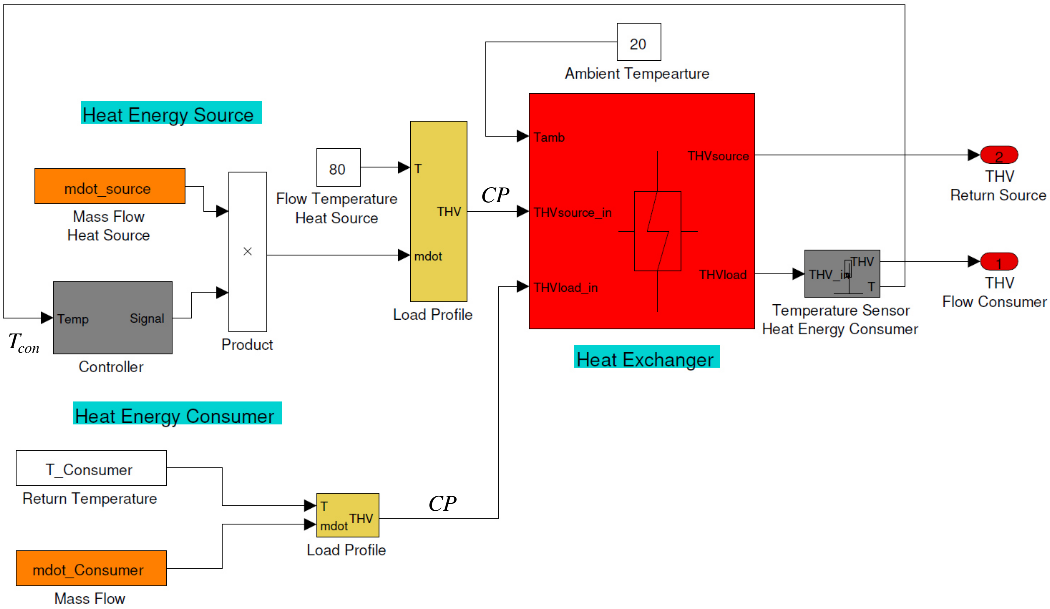


Figure A.22: CARNOT subsystem process heat supply

Process heat source

A heat transfer medium as well as its mass flow and the flow temperature define the process heat source. The mass flow can varies and is therefore time-dependent load profile. The flow temperature is either fix or also a varying temperature profile. A Thermo-Hydraulic vector (THV) transfers all these information — e.g. defined heat transfer medium, mass flow, temperature or pressure — between the model blocks. The heat rate CP (equation (A.6)) represents the medium heat capacity per kelvin temperature change. This is the most important figure in this connection.

$$CP = \dot{m} \times c_p \tag{A.6}$$

A controller (Figure A.22) at the process heat source varies the heat rate. This is with a defined flow temperature T_{def} (reference input) compared to flow temperature T_{con} (control variable) at the process heat consumer. The controller varies with this input the available mass flow of the source with multiplication of a factor between 0 and 1. Figure A.23 illustrates the programme flow of the controller. Mass flow factor at the start time as well as the step size can be applied to each heat source and required precision.

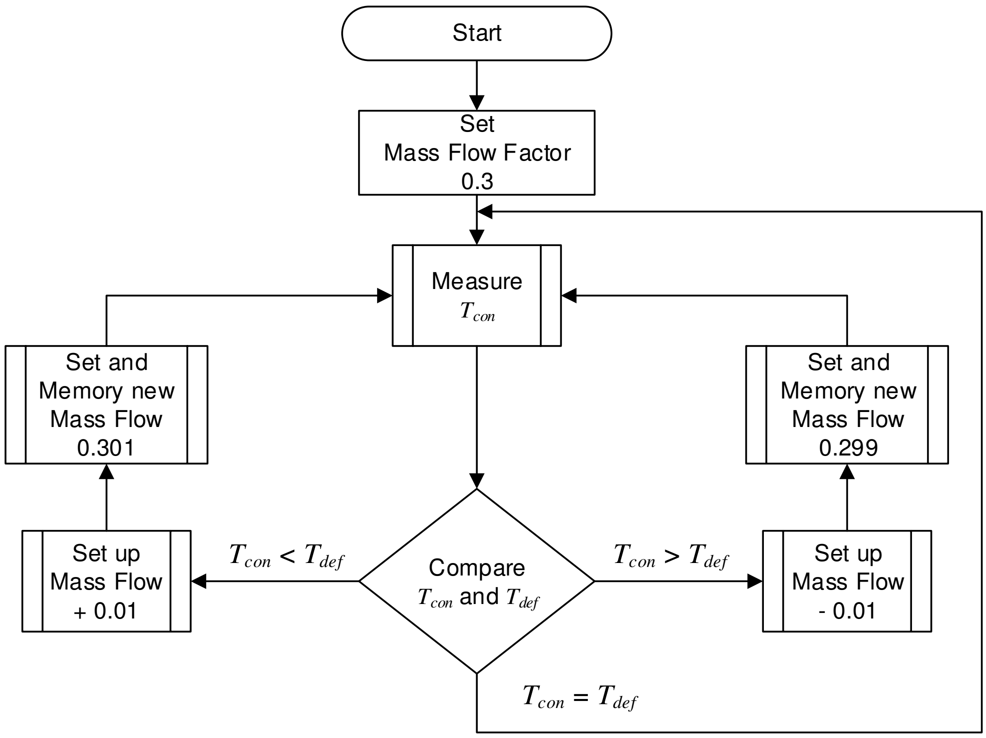


Figure A.23: Programme flow controller

Process heat consumer

The process heat consumer is comparable to the process heat supply defined with the thermodynamic properties of the heat transfer medium, mass flow and return temperature. Mass flow and return temperature are characteristic for each consumer and need specific load profiles. The THV transfers all data to the heat exchanger. An important parameter is additionally the defined flow temperature of the consumer T_{con}. Equation (A.7) is for the heat capacity demand $\dot{q}$.

$$\dot{q} = \dot{m} \times c_p \times (T_{def} - T_{con}) \quad \text{(A.7)}$$

Heat exchanger

The heat exchanger connects supply and consumer and is a model block from the CARNOT blockset (Hafner, 1999). It characterised on the design concept of the cell method. The heat exchanger surface is thereby divided in a number of transfer units (NTU). Each unit is calculated as a single heat exchanger with its specific characteristic. Wagner (2009), Wagner (2011) and VDI (2010) provide respectively equations:

Equation (A.8) describes the overall heat flow rate $\dot{Q}$ and represents the energy to change the temperature of a heat transfer medium form T_1 to T_2.

$$Q = \dot{m} \times c_p \times (T_1 - T_2) \quad \text{(A.8)}$$

An energetic comparison of the hot and cold heat transfer medium in a heat exchanger is possible with the heat capacity rate $\dot{w}_{hot}$ and $\dot{w}_{cold}$ (equations (A.9) and (A.10))

$$\dot{w}_{hot} = \dot{m}_{hot} \times c_p \quad \text{(A.9)}$$

$$\dot{w}_{cold} = \dot{m}_{cold} \times c_p \quad \text{(A.10)}$$

Equation (A.11) and (A.12) represent the heat capacity ratio R_1 and R_2.

$$R_1 = \frac{w_{hot}}{w_{cold}} \tag{A.11}$$

$$R_2 = \frac{w_{cold}}{w_{hot}} = \frac{1}{R_1} \tag{A.12}$$

The number of transfer units NTU_i describes the heat exchanger divided in i sequences, whereas all the sequences are interconnected. The method can be applied with the known parameters of k and A as well as the inlet temperatures (equation (A.13)).

$$NTU_i = \frac{k \times A}{\dot{m}_i \times c_{p,i}} \tag{A.13}$$

The determination of the temperature change for the heat transfer media enables the dimensionless temperature change p_i. Equation (A.14) is for a counter flow heat exchanger. This type is used in all system models.

$$p_i = \frac{1 - \exp\left[NTU_i \times (R_i - 1)\right]}{1 - R_i \times \exp\left[NTU_i \times (R_i - 1)\right]} \tag{A.14}$$

The heat exchanger model of the CARNOT blockset (Hafner, 1999) is developed for a distinction of the *flowtype* parallel (parameter = 0), cross (parameter = 0.5) and counter (parameter = 1). Equations (A.15) and (A.16) consider this fact and provide the necessary dimensionless temperature change psi.

$$p_1 = \exp(-NTU \times (1 + R_1 \times (1 - 2 \times flowtype))) \tag{A.15}$$

$$psi = \frac{(1 - p_1)}{(1 + R_1 \times (1 - flowtype \times (1 + p_1)))} \tag{A.16}$$

Equations (A.17) and (A.18) represent the output temperatures of the hot $T_{hot,out}$ and cold $T_{cold,out}$ medium. These output temperatures were calculated on basis of the dimensionless temperature change psi.

$$T_{hot,out} = T_{hot,in} - psi \times (T_{hot,in} - T_{cold,in}) \tag{A.17}$$

$$T_{cold,out} = T_{cold,in} - \frac{w_1}{w_2} \times (T_{hot,in} - T_{hot,out}) \qquad (A.18)$$

Equation (A.19) provides the specific heat transfer u_a demanding on the actual and the nominal mass flow of the hot and cold heat transfer medium. Basis is the defined maximum heat transfer $k*A$ of the heat exchanger.

$$u_a = k \times A \times \frac{\left(\frac{m_{hot}}{m_{hot,nom}}\right)^{ua,\exp,hot} + \left(\frac{m_{cold}}{m_{cold,nom}}\right)^{ua,\exp,cold}}{2} \qquad (A.19)$$

Solar process heat system

The main components of the solar-thermal subsystem as illustrated in Figure A.24 are the collector and the heat energy storage. Flow controller run the pumps in the collector circuit and the storage charging circuit.

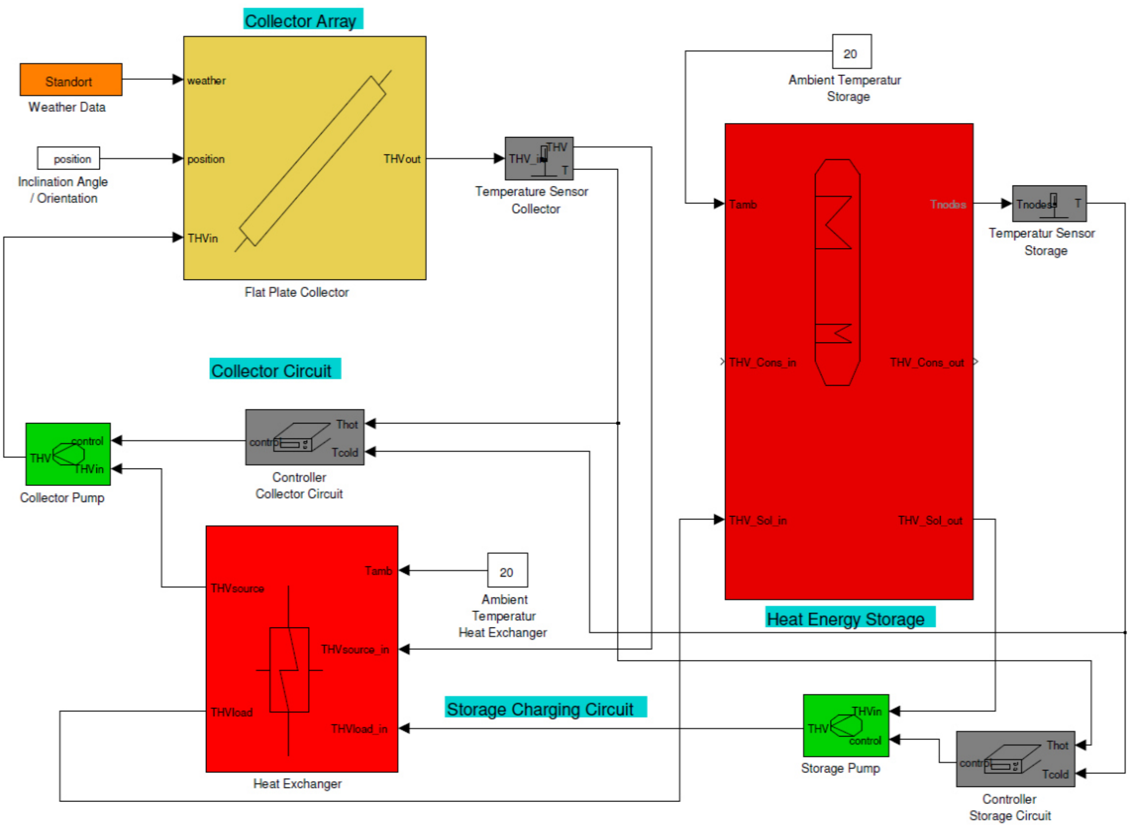


Figure A.24: CARNOT subsystem solar process heat system

A heat exchanger as described in chapter 0 is connection between these two circuits. This model configuration corresponds to a two circuit SPH-system. With the individual parameterisation of each block, it is applicable to each of the system concepts.

Solar collector

Standard for all concepts with solar process heat supply is the implementation of a flat-plate collector. The CARNOT blockset (Hafner, 1999) provides a 'collector_flat_plate' model for this case of application. It is based on a characteristic curve and aims to calculate an output THV with an input THV, the collector position and site specific weather data. An individual defined number of nodes divides the collector along the collector risers. Hence, it is a one-dimensional multinode model (Hafner, 1999). Each node is represented by an energy balance calculated with equation (A.20).

$$c_{col}\frac{dT}{dt} = \dot{q}_{sol} + \frac{\dot{m}\times c}{A_{col}}\times(T_{n-1}-T_n) \qquad (A.20)$$

$$+u_1\times(T_{amb}-T)-u_2(T_{amb}-T)^2$$

$$+u_{wind}\times v_{wind}(T_{amb}+T)+u_{sky}\times(T_{sky}-T)$$

The annual weather data record used for the simulation is each site specific and derived from the meteonorm database (Remund, 2012). It contains information on geographical location as well as average hourly data of direct and diffuse solar radiation, ambient temperature, sky temperature or wind speed. With the Perez sky diffuse model (Duffie, 2006), the direct and diffuse solar radiation on a horizontal surface is transformed to the inclined surface of the collector.

Storage

The storage_multiport of the CARNOT blockset (Hafner, 1999) is a multifunctional storage model. It consist of the storage tank as well as several variations for energy input and energy output. These are a simple pipe connection, a smooth tube heat exchanger, a finned tube heat exchanger and a stratified charging. The design of all parts of the storage model enables an individual configuration. Comparable to the flat-plate collector model, the basic storage concept is a one-dimensional model. The calculation works with a partition of the storage into layers. Each of the layers represents one node and the number of nodes is set case related. The differential equation (A.21) represents the energy balance of one node.

$$\begin{aligned}\rho c \frac{dT_{node}}{dt} &= \frac{(UA)_{loss}}{V_{node}} \times (T_{amb} - T_{node}) \\ &+ \frac{\lambda_{eff}}{dx^2} \times (T_{n+1} + T_{n-1} - 2T_n) \\ &+ \frac{\dot{m}_{up} \times c}{V_{node}} \times (T_{n-1} - T_n) + \frac{\dot{m}_{down} \times c}{V_{node}} \times (T_{n+1} - T_n) \\ &+ \frac{(UA)_{hx}}{V_{node}} \times (T_{hx} - T_n)\end{aligned} \tag{A.21}$$

Equation (A.22) is additional for the calculation of the effective thermal conductivity.

$$\lambda = \frac{A_{C,wall} \times \lambda_{wall} + A_{C,stor} \times \lambda_{fluid} + A_{C,heatex} \times \lambda_{heatex}}{A_{C,stor}} \tag{A.22}$$

<u>Piping</u>

The Integration of piping to the model is necessary for balancing the pipe energy losses. This applies first to collector circuit and storage charging circuit as well as the collector array. The pipe model of the CANROT blockset (Hafner, 1999) considers as a one-dimensional multinode model including the heat capacity of the wall (with pipe material and insulation) and the heat transfer of the mass flow. On basis of the ambient temperature from a site specific weather data record, the energy losses to the environment are determined. The pipe model can be individually divided into a number of nodes. The differential equation (A.21) represents the energy balance of one node.

$$\frac{c_{wall} \times L}{V_{node}} \times \frac{dT}{dt} = \frac{(UA)_{loss}}{V_{node}} \times (T_{amb} - T) + \frac{\lambda}{dx^2} \times (T_{n-1} + T_{n+1} - 2T_n) + \frac{\dot{m} \times c}{V_{node}} \times (T_{n-1} - T_n) \qquad (A.23)$$

System control

The controller of the SPH-system runs the collector circuit and the storage charging circuit. This means first the control of the circuit pumps. A simple controller is available from the CARNOT blockset (Hafner, 1999). It works on temperature comparison and hysteresis with nececary parameters for $deltaT_{on}$ K, $deltaT_{off}$ K and T_{max} $°C$. Signal input is T_{hot} and T_{cold} and output is a on or off signal to the pump. Table A.3 describes the control strategy.

Table A.3: Control strategie (CARNOT blockset)

	strategy	signal output
pump on	$(T_{hot} – T_{cold}) < deltaT_{on}$	1
pump off	$(T_{hot}-T_{cold}) < deltaT_{off}$	0
pump off	T_{hot} v $T_{cold} > T_{max}$	0

Drain tank

The storage_mulitport model block of the CARNOT Toolbox works with a constant volume. Breweries however, use drain tanks with a flexible volume for brew water heating and brew water supply as a kind of storage. This requires a new design approach:

Background is a mass balance of the brew water in the Tank. This considering ingoing mass flow $\dot{m}_{in}$ and outgoing mass flow $\dot{m}_{out}$ with a defined initial storage mass $M_{initial}$. Result is the actual storage mass M_{stor} dependent on a certain time (equation (A.24)). This enables setting parameters for a maximum and minimum fill level as well as fill level during operation.

$$M_{stor}(t) = M_{initial} + \int_0^t \dot{m}_{in} - \int_0^t \dot{m}_{out} \qquad (A.24)$$

The mixing temperature of the brew water in the drain tank is calculated with the rule of mixture from Richmann (Kuchling, 2014). Equation (A.25) describes that temperature dependent on the mass flow into the storage $\dot{m}_{in}$ and the actual mass in the storage M_{stor} with each individual heat capacities and temperatures. The storage temperature $T_{m,stor}$ already considers the temperature loss in fact of energy losses. The mixing temperature (equation (A.25)) is important for the control of hot brew water supply and backup heat.

$$T_m(t) = \frac{\dot{m}_{in}(t) \times c_{in} \times T_{in} + M_{stor}(t) \times c_{stor} \times T_{m,stor}}{\dot{m}_{in}(t) \times c_{in} + M_{stor}(t) \times c_{stor}} \qquad \text{(A.25)}$$

Heat loss $\dot{q}_{loss}$ (equation (A.26)) of the drain tank is determined with the tank surface A, the heat loss coefficient UA_{loss} and the ambient temperature T_{amb} in combination with the mixing temperature T_m. The mixing temperature is in consequence of large mass flow in and out of the storage defined constant. This enables to neglect the heat transfer within the fluid (hot brew water).

$$\dot{q}_{loss}(t) = UA_{loss} \times A_{stor} \times (T_m - T_{amb}) \qquad \text{(A.26)}$$

Figure A.25 gives an overview of the relationships of ingoing mass flow, outgoing mass flow and storage mass as well as the energy loss with the temperature loss.

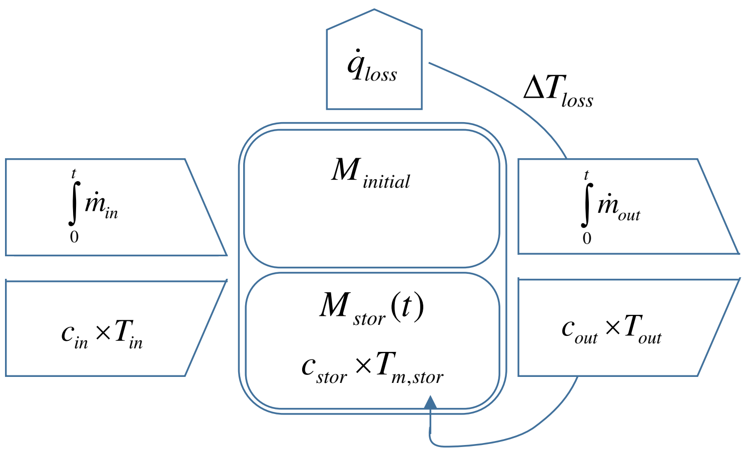


Figure A.25: Flow chart of drain tank

Appendix B Brewery case study

B.1 Energetic analysis – Energy balance

A fossil fuel-fired steam boiler provides the thermal energy at the brewery. The boiler uses mainly gas and, depending on procurement cost, sometimes fuel oil. Electricity is used, to operate the chillers for cooling applications and the air compressors. Based on these facts, the balance area analysis needs to consider fossil fuels and electricity on the input side of the system and finished products — beer and non-alcoholic beverages — on the output side. This balance area as defined in Figure B.1 includes the company plant with all the production facilities, as well as the energy consumed by the plant and the products.

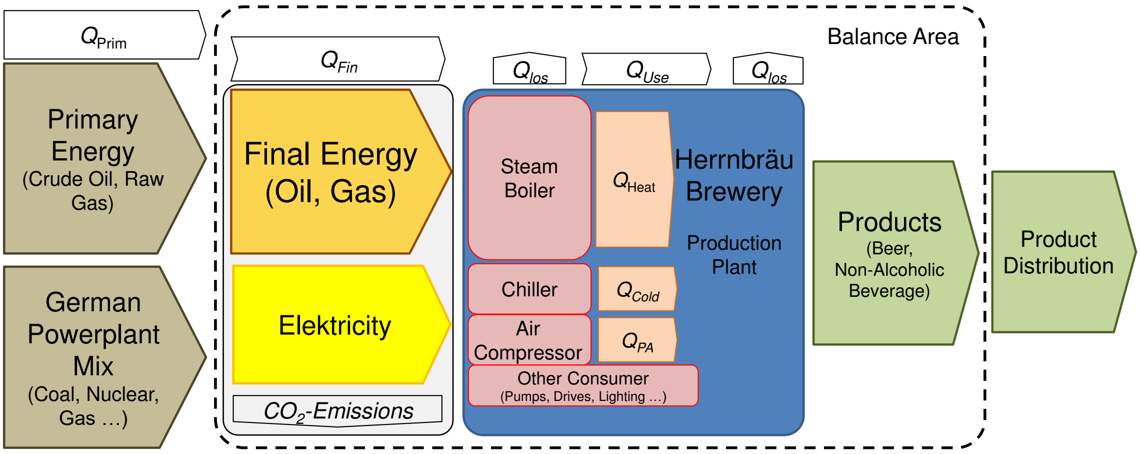


Figure B.1: Definition of balance area at the brewery

An important differentiation at the input side is between primary and final energy. With regard to fuels, this means that only the energetic and exhaust properties of fuel oil or gas as final energy sources are considered (Table B.1). Electricity is a product of the German power plants. Once the balance area and the energy sources are defined, the specific key figures can be defined. Four main figures are considered to describe the energetic and ecological behaviour of the brewery. Table B.2 shows the key figures for fossil energy, process heat and electricity consumption, as well as GHG-Emissions.

Table B.1: Properties of energy sources (cf. GEMIS48, 2013; IINAS, 2012)

	Billing Unit	Calorific value	GHG-Emissions
Fuel Oil	l	10 kWh_{th} l^{-1}	302 g_{CO2Equ} kWh_{Fin}^{-1}
Gas	Nm^3	9.7 kWh_{th} Nm^{-3}	244 g_{CO2Equ} kWh_{Fin}^{-1}
Liquid Gas	Nm^3	30.1 kWh_{th} Nm^{-3}	236 g_{CO2Equ} kWh_{Fin}^{-1}
Biomass	srm	840 kWh_{th} srm^{-3}	35 g_{CO2Equ} kWh_{Fin}^{-1}
Electricity*	kWh	1 kWh_{el} kWh^{-1}	567 g_{CO2Equ} kWh_{el}^{-1}

* German Power Plant Mix 2010

Table B.2: Definition of specific key figures

Category	Meaning	Unit
Energetic	Fossil Energy Consumption per Unit Beer Output	kWh_{fos} hl_{beer}^{-1}
Energetic	Process Heat Consumption per Unit Beer Output	kWh_{th} hl_{beer}^{-1}
Energetic	Electricity Consumption per Unit Beer Output	kWh_{el} hl_{beer}^{-1}
Ecological	GHG-Emissions per Unit Beer Output	kg_{CO2Equ} hl_{beer}^{-1}

The balance period is always one year, from January 1 through December 31. The following balances in Table B.3 and Table B.4 show the changes in energy consumption with GHG-emissions and the production output from 2008–2011.

Table B.3: Energy consumption and GHG-emissions

		2008	2009	2010	2011
Fossil Energy	[MWh]	7,528	7,609	7,463	7,515
Process Heat	[MWh_{th}]	6,967	7,052	6,901	6,989
Electricity	[MWh_{el}]	1,636	1,637	1,612	1,648
GHG-Emissions	[t_{CO2Equ}]	2,920	2,931	2,819	2,815

Table B.4: Production output

		2008	2009	2010	2011
Beer Output	[hl]	116,238	118,421	114,224	119,914
NAB Output	[hl]	68,826	63,982	65,716	70,883

For a distinction of the energy demands for beer and NAB, Kunze (2012) defined a ratio of 5:1. Despite a large fraction of NAB production output, beer production consumes more than 90% of the thermal energy and the electricity. Hence, only the energy consumption and GHG-emissions for beer production are considered. Table B.5 gives the specific key figures for the beer production.

Table B.5: Specific key figures per unit beer production

		2008	2009	2010	2011
Fossil Energy	[kWh_{Fos} hl_{Beer}^{-1}]	58.9	58.9	59.6	57.0
Process Heat	[kWh_{th} hl_{Beer}^{-1}]	54.6	54.6	55.1	53.0
Electricity	[kWh_{el} hl_{Beer}^{-1}]	12.8	12.7	12.9	12.5
GHG-Emissions	[kg_{CO2Equ} hl_{Beer}^{-1}]	22.2	22.0	21.9	21.3

Important for an evaluation of the total energy efficiency of a company is a benchmark with the specific key figures. The benchmark in this case is an average brewery defined by Kunze (2012). Table B.6 shows a deviation for process heat of 10% and for electricity of 9% to the benchmark. The deviation to the optimum brewery (

Table B.7) is with 69% for process heat and 50% for electricity much clearer. These both is indicator for the optimisation potential. However, conclusions on critical area are not able with this company analysis.

Table B.6: Benchmark with an average brewery 250,000 hl_{beer} a^{-1} *

		Average Brewery (Benchmark)	Brewery (Case study)	Deviation
Process Heat	[kWh_{th} hl_{Beer}^{-1}]	48.0	53.0	+ 10%
Electricity	[kWh_{el} hl_{Beer}^{-1}]	11.4	12.5	+ 9%

*(Kunze, 2012)

Table B.7: Benchmark with an optimum brewery 250,000 hl_{beer} a^{-1} *

		Optimum Brewery (Benchmark)	Brewery (Case study)	Deviation
Process Heat	[kWh_{th} hl_{Beer}^{-1}]	31.4	53.0	+ 69%
Electricity	[kWh_{el} hl_{Beer}^{-1}]	8.3	12.5	+ 50%

*(Kunze, 2012)

For both, fossil energy and electricity, a negative correlation is between energy consumption and production volume (Figure B.2). The lowest overall production volume in 2010 was connected to the highest specific energy demand and the highest production volume in 2011 with the lowest energy demand. This effect applies not for the GHG-Emissions because the Emissions for electricity vary from year to year in fact of a changing power plant mix in Germany.

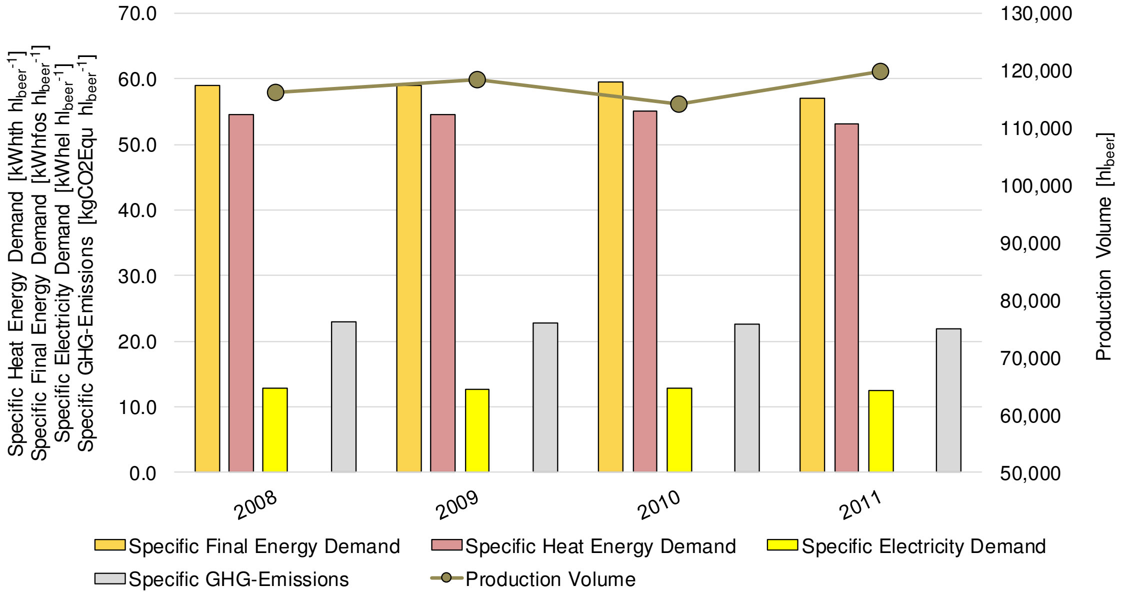


Figure B.2: Development of specific key figures

B.2 Energetic analysis – Energy distribution networks

Three networks (Table B.8) distribute thermal energy and air compressors supply pressurised air with a network. Although no continuous energy data recording is available, the brewery size allows a comparatively detailed analysis of energy demand and distribution. Manual data recording, calculations and temporary data recording using mobile measurement equipment provide the.

The main source for process heat supply is the steam boiler with the steam distribution network (Table B.8). The steam boiler supplies 5,970 MWh_{th} a^{-1} (2010) process heat to the network at 170°C to the main line. This is reduced to 134°C at the sections and supplied to processes and applications. The network handles process heat demand for a range of conditions, from high temperatures and high heating capacity to low temperatures and low heating capacity.

Table B.8: Steam distribution network

Energy Generation	Heat Transfer Medium	Temperature Level	Process Heat
Steam Boiler	Steam	170°C / 134°C	5,970 MWh_{th} a^{-1}

Figure B.3 shows a load profile of steam distribution with the heating capacity from the steam boiler. It represents all production activities (brewing, filling, cleaning) with process heat demand from Sunday evening to Thursday. This load profile is typical for the brewery and repeats in the same course with slightly changes of heating capacity depending direct on production volume.

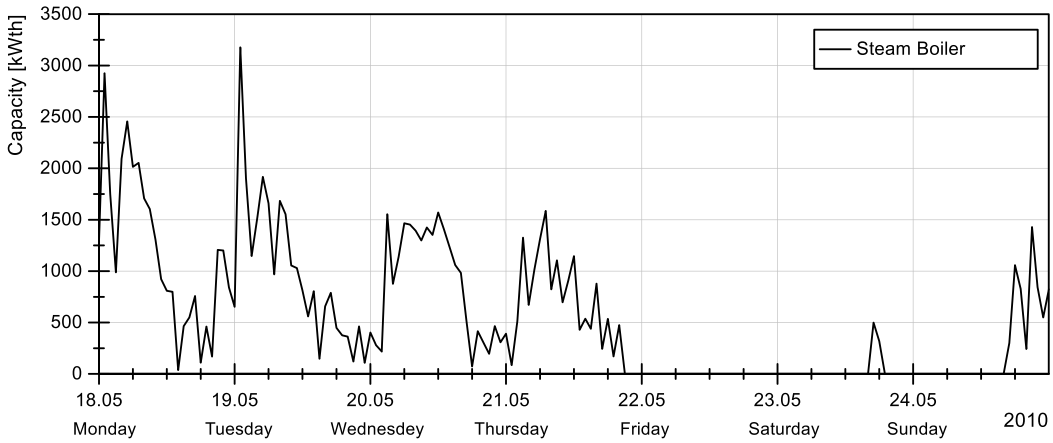


Figure B.3: Steam heat capacity for the complete brewery (exemplary production week)

Main heating utility is a gas fired steam boiler with maximum fuel consumption of 7,120 kW and a steam capacity of 8 t h^{-1} at $p_{abs} = 10$ bar (Loos, 1973). In operation the boiler provides steam at 170°C and p_{abs} = 7 bar. A second heat source is the waste heat recovery from wort cooling. The process lasts for 1 hour and cools down the wort from 96–25°C. Regarding the brewing capacity of 300 hl, a heat capacity of 2.490 kW_{th} is available.

The steam distribution network operates with two level: As Figure B.4 illustrates, a main pipe distributes the steam from the boiler to the energy consumers. They differ from the production sections and are the brew house, CIP process, bottle cleaning, keg cleaning / Pasteur, various applications and the LGH-supply. The steam is there reduced before the brew house to a second level at p_{abs} = 3 bar and 134°C before entering the consumer. All the other steam energy consumers get steam at p_{abs} = 7 bar and 170°C.

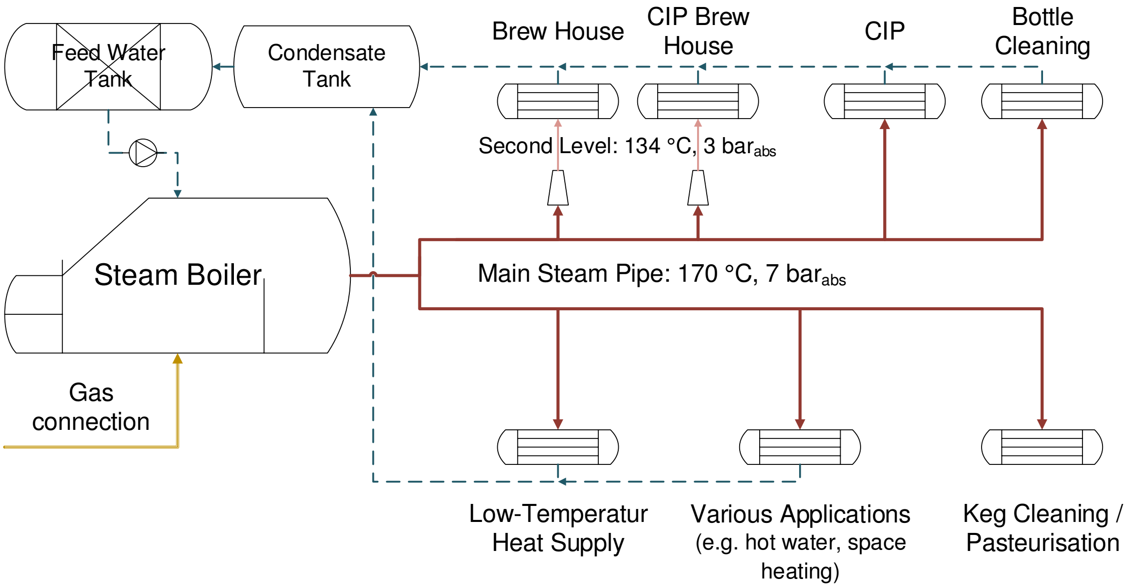


Figure B.4: Schematic of steam distribution network

Hot water from low-grade heat supply is for processes in the brew house and cleaning applications (CIP). The energy supply from waste heat is not enough to cover all the demand of 2,450 MW_{th} (2010). The steam distribution network supplies 1,520 MW_{th} (2010). Steam energy is back-up and ensures always the right conditions. Hence, it is essential for this system for the hot water supply. Preparation and supply of hot water (Figure B.5) is an important part of the process heat system of the brewery.

This supply system is not comparable to a conventional energy distribution network with a circulating heat transfer medium and heat exchanger for energy supply do not exist. The hot water is of food quality and direct used for mashing and lautering in the brew house, and several cleaning applications. Consequently, the fill level of the drain tank varies with available waste heat and hot water demand at a defined level.

The LGH-supply provides about 36% of the total process heat demand of the brewery. Particular is the heat transfer medium hot brew water. This does not circulate within a network but us directly used at the processes and applications.

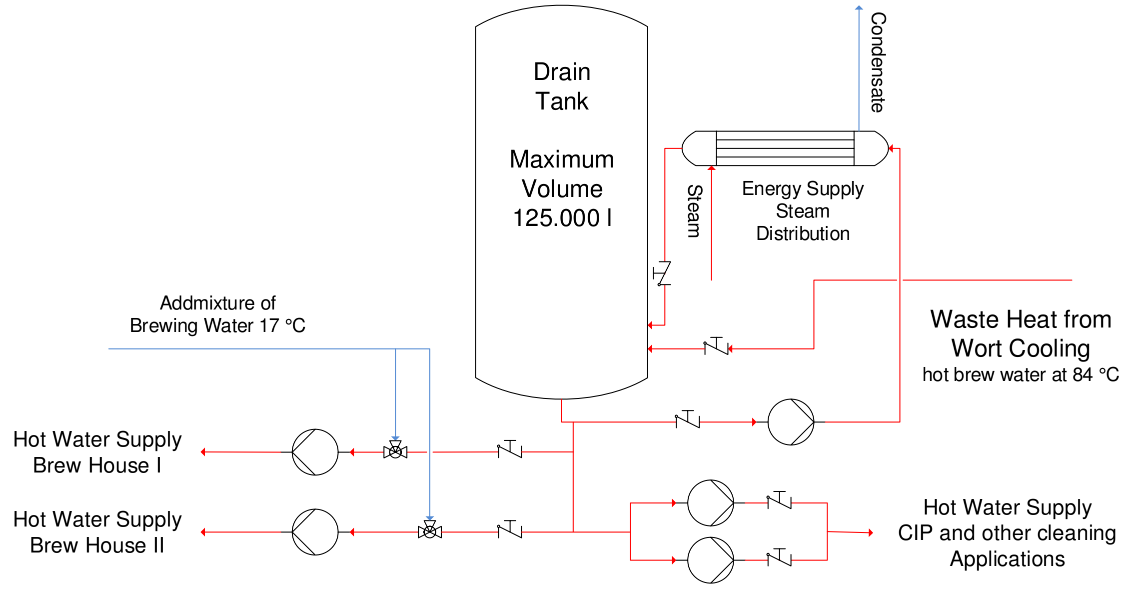


Figure B.5 Schematic of low-grade heat supply

The temperature level of 84°C depends on the supply of the lautering process (Table B.10). The source of this heat supply is heat recovery from wort cooling with 930 MWh_{th} a^{-1} in 2010 complemented with heat from the steam energy supply (Table B.9).

Table B.9: Low-grade heat supply

Energy Supply	Heat Transfer Medium	Temperature Level	Process Heat
Steam Distribution	hot brew water	84°C	1,520 MWh_{th} a^{-1}
Heat Recovery			930 MWh_{th} a^{-1}

The steam distribution supplies for example the boiling processes, CIP and the bottle washing machine (Table B.10). On the one side, boiling processes need the temperature level and heating capacity of the network. On the other side, CIP and bottle washing machine can also supplied with lower temperatures, what is important for optimisation.

The processes and applications connected to the LGH-supply directly use the hot brew water. Main component of the network configuration is a drain tank with a volume of 125,000 l. It stores hot brew water heated from wort cooling and the additional hot brew water heated from steam distribution. That heat supply provides already an interesting configuration for additional heat recovery and solar process heat. It is basis for reconfiguration and concept development.

Table B.10: Energy distribution with exemplary processes

	Supply Temperature	Processes	Process Temperature
Steam Distribution Network	134°C	Wort Boiling (including evaporation)	78–100°C
		Mash Boiling	72–98°C
		CIP	50–95°C
		Bottle Washing Machine	72–82°C
Low-Temperature Heat Supply	84°C	Mashing In	35°C / 60°C
		Lautering	78 °C
		CIP (Clear Water Cleaning)	<84 °C

The ice water network supplies about 845 MWh_{th} a^{-1} cooling energy required by processes. Space cooling is achieved with direct evaporating refrigerants (NH_3) and 230 MWh_{th} a^{-1}. The compressors of both systems need a propulsion energy of 285 MWh_{el} a^{-1} in 2010 (Table B.11). This is just important in process of the optimisation.

Table B.11: Cooling distribution

Energy Generation	Heat Transfer Medium	Temperature Level	Propulsion Energy
Chillers	Ice Water	0–1°C	285 MWh_{el} a^{-1}
Chillers	NH_3	-3°C	

Propulsion energy of the chillers is just one part of the total electricity demand. Figure B.6 illustrates the electric power demand of the whole brewery. This load profile shows a similar course compared to steam heating capacity, but with a base load also on weekend. This is a result of continuous cooling and pressurised air demand.

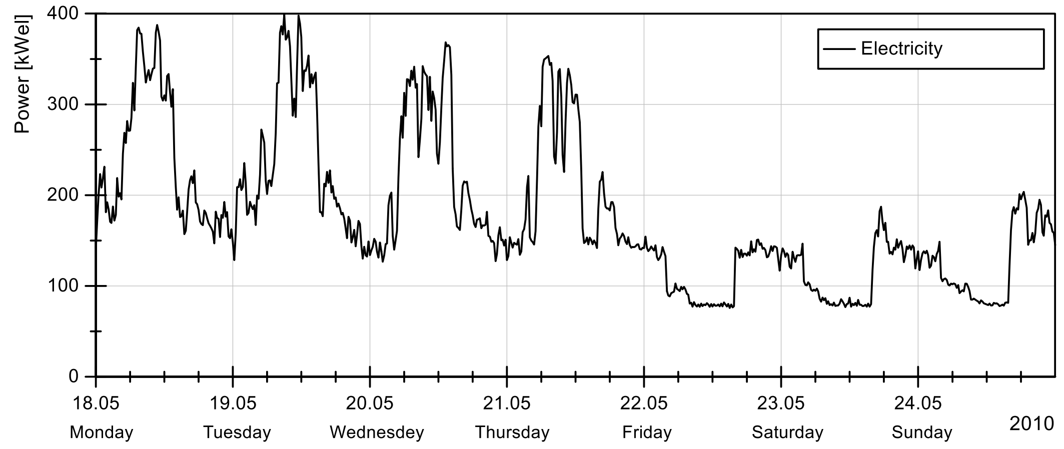


Figure B.6: Electricity power demand (exemplary production week)

The weekly load profiles of energy demand are mainly driven by the regular brewing operation. The annual load profile of process heat demand however, is more continuously than the production volume of the brew house. As Figure B.7 illustrates, the monthly course is connected to the production volume between April and August.

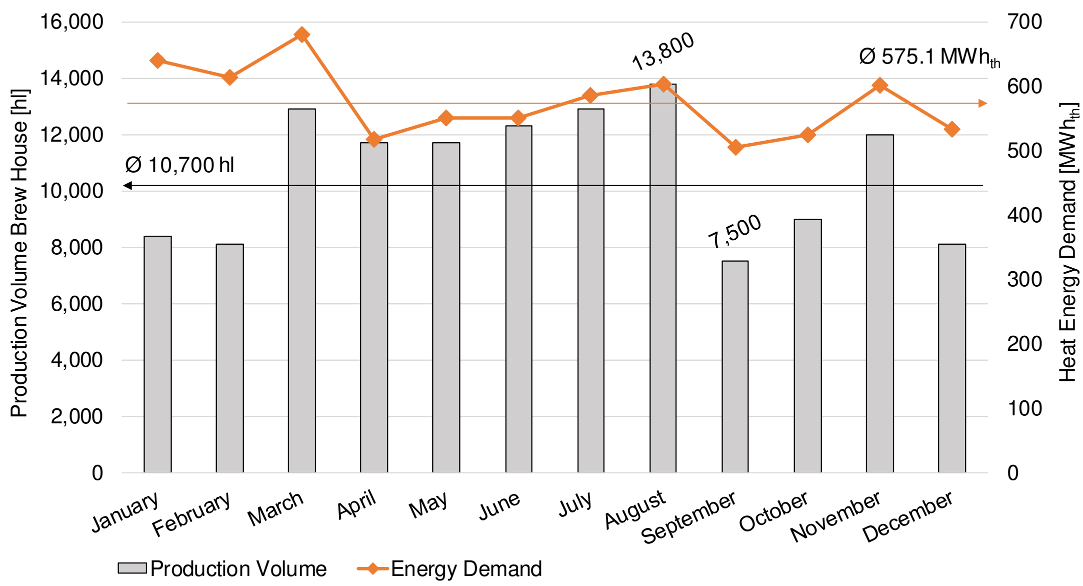


Figure B.7: Production volume and process heat demand

From January to March and September to December, the heating of buildings influences the energy demand. Result in these periods is an increasing energy demand in comparison to the production volume. The production volume is varying by about 29% from the average value and has a maximum of 13,800 hl in August and a minimum of 7,500 hl in September. The process heat demand is varying lower by about 15% from an average. Maximum energy demand is here in March and minimum in September. Additionally, the production volume follows a curve that is quite comparable to the availability of solar radiation in central Europe throughout the year. This is typical for the brewing sector and favours solar-thermal applications for supplying production processes.

B.3 Energetic analysis – brewery sections

Independent from the two product groups of top-fermented and bottom-fermented beer, a brewery can be separated into several sections. The focus of that discussion is the energy demand of the sections. Figure B.8 illustrates five main sections for a common brewery and their associated energy demand. A further distinction is with process heat consuming ‘hot area’ and cooling energy consuming ‘cold area’. A section in this connection can be both (e.g. Brewhouse).

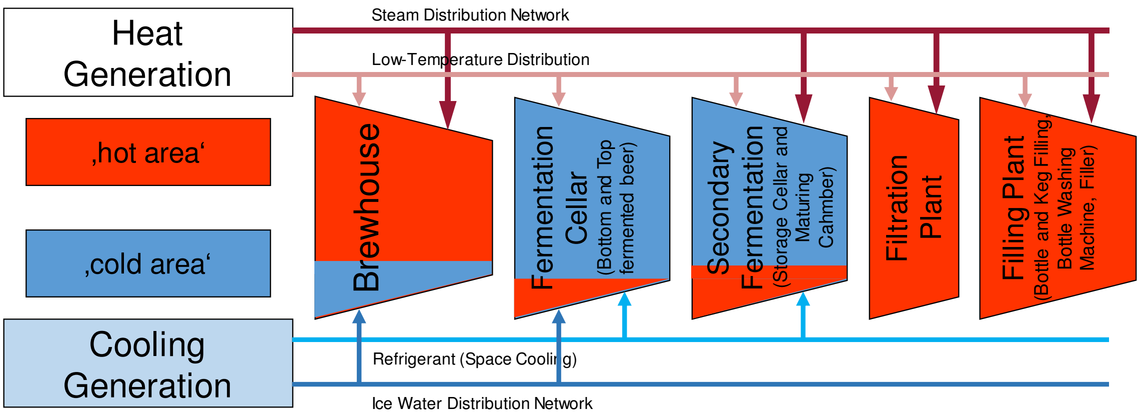


Figure B.8: Production sections and energy supply

Brewhouse

The brewhouse is the centrepiece of a brewery and section for wort processing. Wort is base product of all kinds of beer and processed in several steps. Wort processing consists mainly of boiling processes at different temperatures (Table B.12). Hence, the brew house is the largest process heat-consuming section in a brewery. Additionally, wort cooling requires cooling energy because the hot wort must be cooled down before it is transferred to the fermenting cellars.

Table B.12: Process temperature in the brewhouse

	Min. Temperature	Max. Temperature
Process Heat	35°C	140°C
Cooling	7°C	18°C

Fermentation Cellars

Depending on top-fermented or bottom-fermented beer, two different kinds of fermentation cellars are required. In the fermentation cellars, the wort is mixed with yeast and matures to beer. Cooling energy is the primary energy required in both types of cellars. The necessary temperature level for bottom-fermented beer is much lower; therefore, the specific cooling energy demand is higher. In the case of beer processing, the fermenting cellars are an exclusively cold section and do not need process heat (Table B.13).

Table B.13: Process temperature in the fermentation cellars

	Min. Temperature	Max. Temperature
Process Heat	-	-
Cooling	7°C	24°C

Secondary Fermentation

The secondary fermentation is also divided into areas for top-fermented and bottom-fermented beer. Similar to the fermentation cellars, the cooling demand for bottom-fermented beer is higher. However, in contrast to the exclusive cooling energy demand within the fermenting cellars (Table B.14), the temperature level for secondary fermentation of top-fermented beer sometimes requires process heat, depending on the ambient temperature.

Table B.14: Process temperature during secondary fermentation

	Min. Temperature	Max. Temperature
Process Heat	-	20°C
Cooling	-2°C	20°C

Filtration Plant

During filtration, the matured beer is separated from the yeast residuals and other suspended solids before the filling. Different types of filter facilities are in use. Filtration itself is a process without either process heat or cooling energy demand.

Filling Plant

The filling section is behind the brew house the second-largest consumer of process heat. The beer is poured into bottles or kegs and finished for distribution. Energy is used for bottle and keg cleaning, keg sterilisation as well as cleaning of the bottle boxes. Breweries that produce non-alcoholic beverage also consume process heat for pasteurising. Temperature levels for process heat in Table B.15 include all the mentioned applications. The bottle washing machine is the main energy consumer, requiring a temperature level of 58–82°C. The exact temperature level depends on the machine, the kind of bottle (glass or PET) and the cleansing agent. For keg sterilisation and pasteurisation, steam is often directly used. There is no cooling demand within the filling section.

Table B.15: Process temperature for filling

	Min. Temperature	Max. Temperature
Process Heat	~ 50°C	~ 130°C
Cooling	-	-

Table B.12 to Table B.15 show the required process temperature and consider only the production processes for processing beer. Other applications such as cleaning of brewing equipment and heating of the manufacturing facility or space will be described below.

Cleaning-in-Process (CIP)

Besides the process heat and cooling for processing beer, there are additional energy consumers in a brewery. Cleaning and cleaning equipment are very important in the food industry. CIP equipment ensures the required hygiene standards and are defined as an additional section. CIP is very flexible and offers various cleaning processes adapted to the specific equipment or facility.

Breweries use single system for each section or centralised systems for the whole company. Generally, CIP is known as a large process heat consumer at low temperatures (Table B.16), depending on the cleaning process itself, as well as the specific abilities of the used cleaning agent.

Table B.16: Process temperature for CIP

	Min. Temperature	Max. Temperature
Process Heat	40°C	90°C
Cooling	-	-

Space Heating (SH) and Service Hot Water (SHW)

The last section defined with regard to thermal energy supply is the one including SH and the DHW supply. SH in this connection means process heat for both offices and production (Table B.16). SHW is mainly required in social rooms for washing and showering.

Table B.17: Temperature for SH and SHW (including manual washing)

	Min. Temperature	Max. Temperature
Heating	20°C	65°C
Cooling	-	-

The temperature shown in Table B.12 to Table B.17 are general and intended to be understood as average values for the brewing industry. With regard to a solar process heat, the temperature levels needed in the different sections are very important. The filling section with the bottle washing machine, cleaning applications, and the SHW supply provide many possibilities for the use of solar process heat.

B.4 Energetic analysis – energy consumer

In contrast to the five production sections, four main heat-energy-consuming areas are defined: brewhouse, CIP, bottle cleaning, and various applications. The Brew house and bottle cleaning (filling section) are comparable to the defined production sections. In contrast to that, the energy consumption of CIP and various applications is not assignable to a specific area and used over the whole production plant. As Table B.18 illustrates, all areas are largely supplied by the steam boiler. The LGH-supply (hot water preparation) is not defined as consuming area in this case, because it supplies again process heat to some of them.

Table B.18: Energy consuming areas and steam energy demand

	MWh_{th}	Proportion [%]	Direct Steam Energy Supply
Total Process Heat	6,901	100	5,970
Brew House	2,267	32.9	1,347
CIP	1,430	20.7	355
Bottle Cleaning	885	12.8	885
Space Heating / Hot Water	1,508	21.9	1,293

The brewhouse needs 1,347 MWh a^{-1} of energy from steam distribution. This is about 22.6% of the brewery's total steam energy. Heat up and boiling need large amounts of process heat and high heating capacity (Table B.19). The target temperature T_{tar} reaches just 100°C, but with respect to energy demands and the batch period, it is only feasible with large energy generators.

Table B.19: Specification of brew house processes (examples)

	Heating Capacity	Process Heat	Batch Period	T_{tar}
Heat up Mash *(top fermented)*	1,680 kW	520 kWh_{th} bat^{-1}	20 min.	52°C
Heat up Wort	2,040 kW	1,015 kWh_{th} bat^{-1}	45 min.	98°C
Heat up Wort	1,615 kW	1,270 kWh_{th} bat^{-1}	70 min.	100°C

Additional to the heating capacity of each process, there is an accumulation of this capacity in fact of parallel running processes. Figure B.9 illustrates the calculated heating capacity of the brew house at a regular production day. The three mashes start time-shifted and require a heating capacity of about 2,000 kW_{th}, when mash and wort heating run parallel. Basis for the calculation in this case are only processes with direct steam energy supply (cf. Figure B.13).

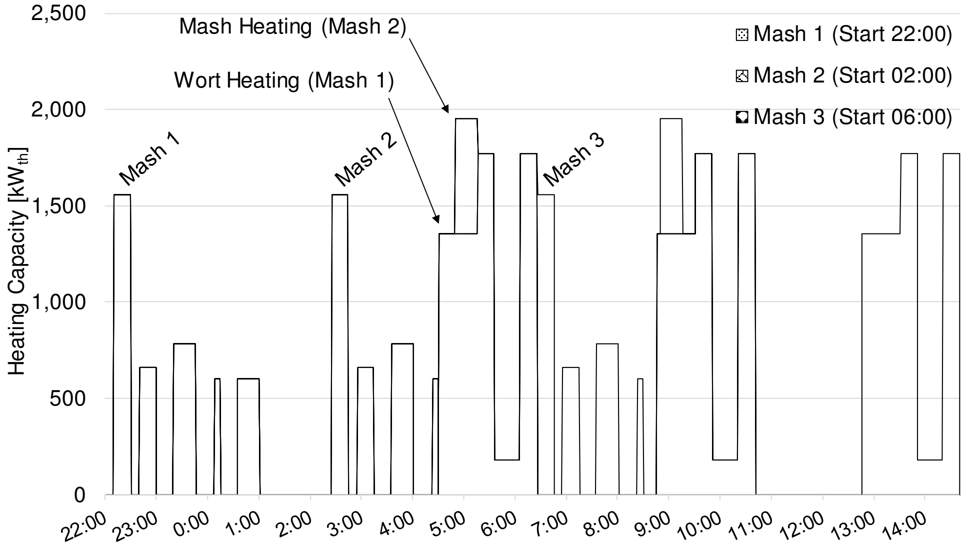


Figure B.9: Steam heat capacity of the brewhouse

Cleaning is important in food processing companies. Five CIP facilities are therefore in operation at the brewery, one for each production section. Each CIP cleans different production equipment with various cleaning programmes. Hence, the cleaning period and process heat demand depend strongly on the equipment to be cleaned. Large amounts of process heat for cleaning are supplied via the LGH-supply for mixing acid and brine cleaning fluids as well as rinsing with hot water. Heating up the fluids to the target temperature requires about 6% of the brewery's total steam energy and 25% of the total CIP energy needs, which is 355 MWh_{th} a^{-1} of steam energy. Figure B.10 illustrates an exemplary cleaning process for brew house equipment.

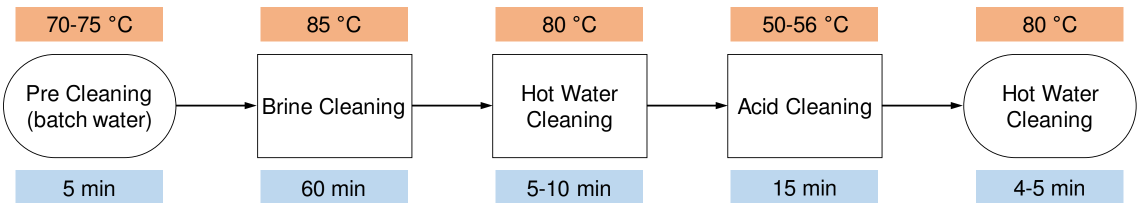


Figure B.10: Cleaning process scheme for mash equipment and wort kettle

Figure B.11 illustrates exemplary the heating capacity for cleaning mash tun and mash kettle in the brewhouse. It reaches about 180 kW_{th} over the cleaning period.

The peaks at the beginning and ending of each cleaning period is an effect of the heat exchanger switch on and off behaviour.

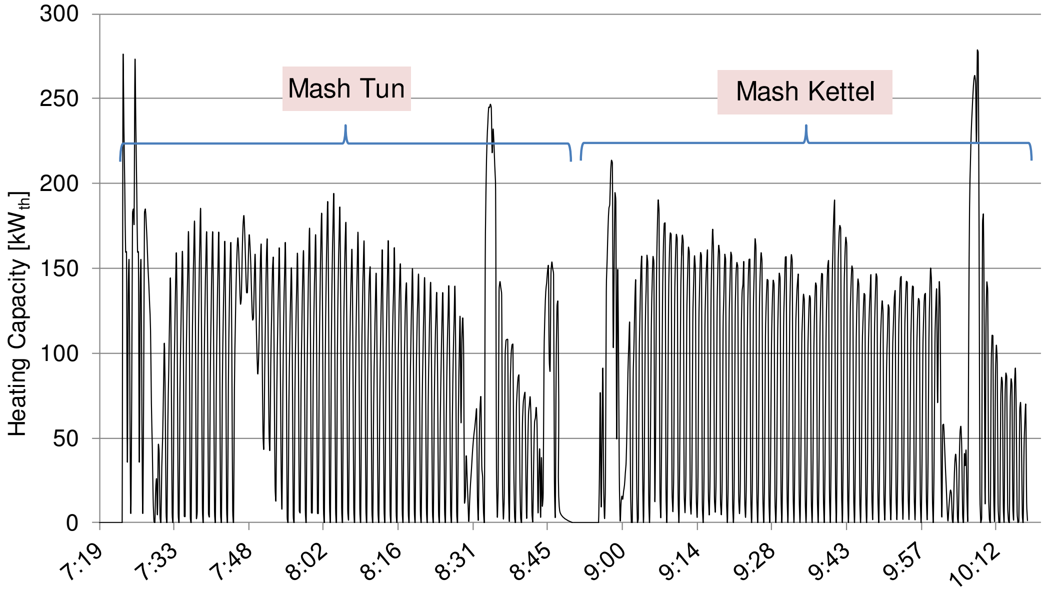


Figure B.11: Steam heat capacity of brewhouse CIP

The cleaning process is divided into several phases. Each step takes a defined time at a certain temperature level. All the fluids are prepared with hot brew water from the LGH-supply. Hence, the steam energy necessary for preparation of the fluids is low compared to the hot brew water consumption. Steam is mainly consumed during the cleaning phases to maintain the specified temperature level. Each single phase is a closed-loop process. The cleaning fluid is transferred into the equipment to be cleaned and pumped continuously in a cycle.

The bottle washing machine is located in the filling section of the brewery and operates only if the bottle filler runs. Bottle washing machines permanently consume energy during operation (Figure B.12), but have to be heated up with constant heating capacity over a period of about one hour due to the huge thermal capacities of the machine itself, as well as the cleaning fluid in the machine. The heat exchanger behaviour of the bottle washing machine is comparable to the heat exchanger behaviour of the CIP facility described before. The bottle washing machine requires 14.8% of the brewery's total steam energy supply, which is 885 MWh_{th} a^{-1} and making it the largest single energy consumer.

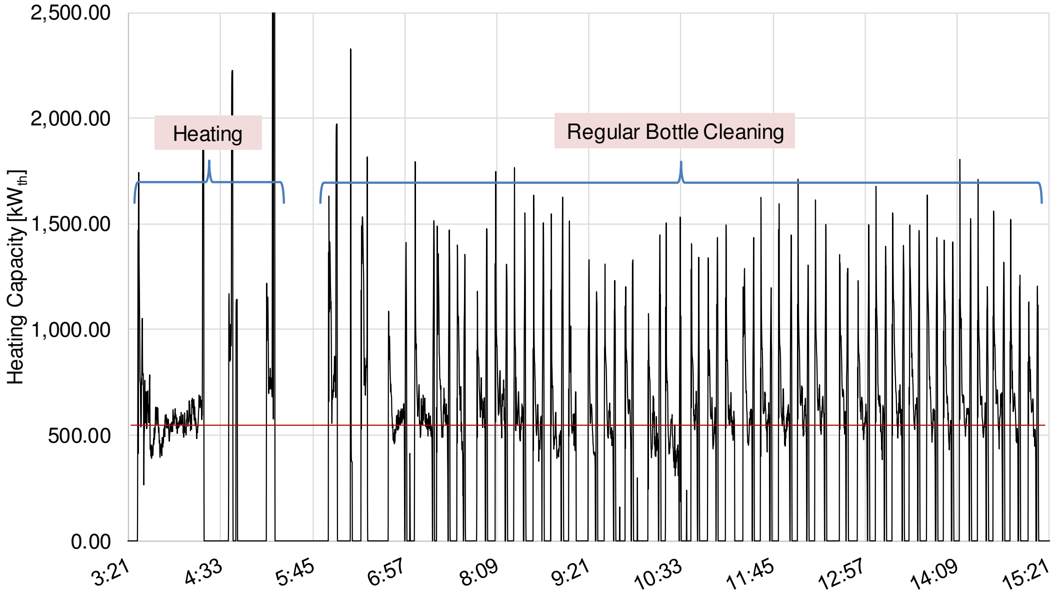


Figure B.12: Steam heat capacity of bottle washing machine

In summary, the process analysis results in good conditions for LGH-sources, such as SPH-systems and heat recovery measures. More than 70% of the final energy demand is required for processes with a temperature level below 85°C and at a feasible power demand. As Table B.20 illustrates, the most promising are the cleaning applications. An additional high potential for solar process heat and heat recovery shows the LGH-supply with the already connected CIP, mashing in and lautering process.

Table B.20: Low-grade heat processes

	Max. Heating Capacity	Process Heat Demand	T_{tar}
CIP	350-700 kW_{th}	355 $MWh_{th}\,a^{-1}$	50-85°C
Bottle Cleaning	700 kW_{th}	885 $MWh_{th}\,a^{-1}$	82°C
CIP	545 kW_{th} (preparation of hot water)	1,075 $MWh_{th}\,a^{-1}$	85°C
Mashing in		320 $MWh_{th}\,a^{-1}$	35-60°C
Lautering		600 $MWh_{th}\,a^{-1}$	76°C

The consumer set parameters for the energy demand on a LGH-supply. This are target temperature, heat capacity and duration of heat supply. Table B.21 gives and overview of the heat consumer requirements at the brewery. The target temperatures range from 20–100°C. The heating capacity is from 50–2,045 kW_{th}

and supplied with hot water or steam. Each consumer is assigned to a heat source. Another important aspect to consider for optimisation is a multiple use of equipment. Mashing, mash heating and mash boiling is all in the same vessel. Hence, the energy supply cannot be defined exclusively for the process but for the equipment.

Table B.21: Energy consumer at the brewery

	Target Temperature $T_{\max}$	Heating Capacity $\dot{Q}_{th,\max}$	Duration t_{dur}	Heat source
Mashing	60°C	*direct use*	15 min	hot water
Mash Heating	98°C	1,680 kW	5–26 min	steam
Mash Boiling	100°C	1,680 kW	5–15 min	steam
Lautering	76°C	*direct use*	50–70 min	hot water
Wort Heating	98°C	2,045 kW	45 min	steam
Wort Boiling	> 100°C	1,615 kW	70 min	steam
CIP 1 + 2	60°C	380 kW	*dependent on individual program*	steam + hot water
CIP 3 + 4	85°C	700 kW		
CIP 5	90°C	350 kW		
Bottle Cleaning	85°C	700 kW	4–10 h d^{-1}	steam
Keg Cleaning	170°C	*direct steam injection*		steam
Crate Cleaning	84°C	*direct use*		hot water
Pasteur	170°C	*direct steam injection*		steam
Space Heating (production, storage)	20°C	30–50 kW	*as required*	steam

The identification of similar consumer groups regarding LGH-supply is helpful for an optimisation. In case of the brewery, the maximum target temperature is therefore the first parameter (Table B.22).

Table B.22: Consumer croup cleaning and space heating

	Target Temperature $T_{\max}$	Heating Capacity $\dot{Q}_{th,\max}$	Reconstruction Reconfiguration
Space Heating (production, storage)	20°C	30–50 kW	*heating technology*
Cleaning	90°C	350–700 kW	*heat exchanger*

Space heating ensures an ambient temperature of 20°C for some parts of the production area. As the existing air heat exchangers work with steam, a reconstruction would be necessary to enable hot water supply. Market available systems work with flow temperature of 70°C (Wolf, 2014).

Cleaning represents a broad range of applications with CIP equipment and bottle washer. The maximum target temperature is up to 90°C. Cleaning in this connection does not include the direct use of hot water.

A LGH-supply can supply both, space heating and cleaning. However, this requires a system with circulating heat transfer medium and a reconfiguration of heat exchanger technology.

A direct use of hot brew water is common in breweries and necessary for *brewing process* and *cleaning*. Mashing temperature is at 35°C and 60°C. Hot brew water at 84°C is therefore mixed with cold brew water. Lautering needs at least a temperature of 76°C and uses the hot brew water at 84°C. A large volume of hot brew water is for the several cleaning applications. It is also used at 84°C for clear water cleaning and rinsing of different equipment, e.g. the bottle filler. The consumption of hot brew water from LGH-supply was 30,023 m³ in 2010 (Table B.23).

Table B.23: Consumer of hot brew water from low-grade heat supply

	Target Temperature T_{max}	Hot Brew Water Temperature T	Hot Water Volume V
Mashing	35°C 60°C	84°C	4,102 m³
Lautering	76° C	84°C	7,704 m³
Cleaning	50–70°C	84°C	18,217 m³

Target temperatures for mash heating and boiling as well as wort heating and boiling are too high for LGH-supply. Mash tun, mash kettle and wort kettle are equipped with steam heat exchangers. Hot water supply technologies (> 100°C) are not common for brew house equipment today. Steam is also necessary for the direct use of keg cleaning and pasteurising.

The Sankey diagram in Figure B.13 summarises the energetic analysis and shows energy consumers and energy consuming area.

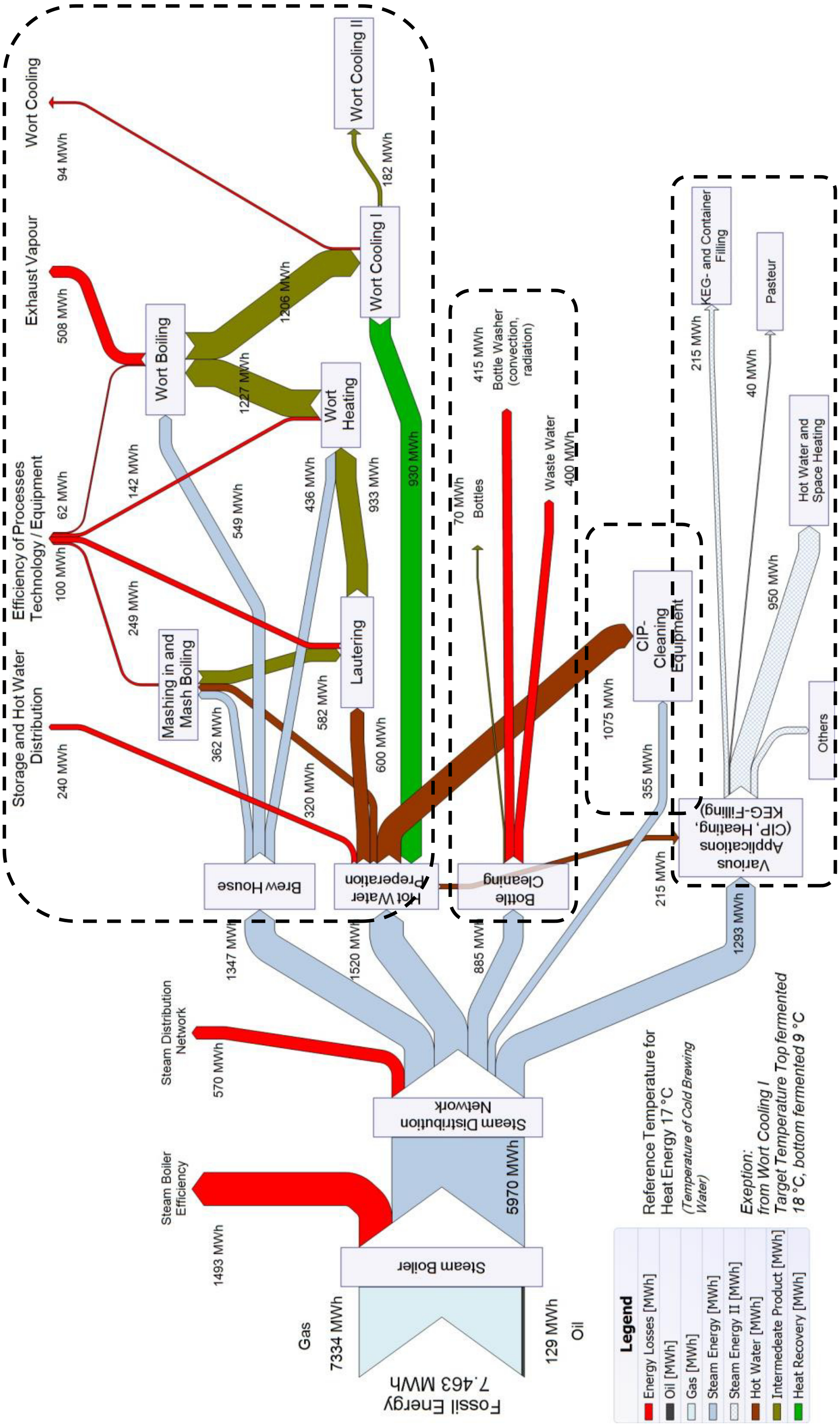


Figure B.13: Sankey diagram of the brewery

B.5 Energetic optimisation – analysis of waste heat sources

Table B.24 shows parameters of *wort cooling*. The heat capacity is at 2,490 kW_{th}. With a duration of 60 min $batch^{-1}$ and a defined transmission efficiency of 0.9 about 2,385 kWh_{th} of heat energy is available. The integrated heat exchanger technology provides in combination with the mass flow hot water at 84°C.

Table B.24: Parameters wort cooling process

Start Temperature	T_{start}	96°C
Target Temperature	T_{tar}	25°C
Mass Flow	$\dot{m}_{med}$	~ 8.3 kg s^{-1}
Specific Heat Capacity	$c_{p,med}$	~ 4,2 kJ kg^{-1} K^{-1}
Duration	t_{dur}	60 min

The *wort boiling processes* aims is to remove undesirable substances. This happens with the evaporation of a defined volume of the wort at ambient pressure and a temperature of 100°C. The evaporation rate is about 1,440 kg $batch^{-1}$, what is also the resulting condensation rate. With the parameters of Table B.25, a heat capacity of 775 kW_{th} is available. Based on the defined transmission efficiency of 0.9, this is 815 kWh_{th} of heat energy. A kettle vapour condenser needs to be retrofitted for that heat recovery. This enables preheating of cold brew water to a temperature between 80–97°C (Kunze, 2010; Thüsing, 2000) and is sufficient for the LGH-supply at the brewery.

Table B.25: Parameters wort evaporation process

Evaporation Temperature	T_{evap}	~ 100°C
Mass Flow	$\dot{m}_{med}$	0.343 kg s^{-1}
Heat of Evaporation	r	2,260 kJ kg^{-1}
Duration	t_{dur}	70 min

For both, heat recovery from *wort cooling* and *vapour condensing* the annual capacity is based on the number of brews (batches). This was at 428 in 2010.

Two configurations of chiller systems provide space cooling and ice water. Propulsion energy comes from piston compressors and the refrigerant is each ammonia. Table B.26 shows the operating conditions of the two chiller systems.

Table B.26: Operating conditions chiller systems

		Space Cooling	Ice Water
Cooling Capacity	$\dot{Q}_{th}$	154 kW_{th}	409 kW_{th}
Propulsion Power	P_{el}	58 kW_{el}	140 kW_{el}
Evaporation Temperature	T_{cond}	- 2°C	- 2°C
Condensation Temperature	T_{evap}	14°C	21,5°C
Refrigerant Mass Flow	$\dot{m}_{ref}$	0.13 kg s^{-1}	0.35 kg s^{-1}
Hot Gas Temperature	T_{gas}	33°C	52°C

Heat recovery potentials depends on the hot gas temperature and the refrigerant mass flow. Space cooling provides a heat recovery potential of 4.3 kW_{th} with a defined deheating temperature of 20°C (Table B.27). In combination with the hot gas temperature, a heat recovery is not practical in this case. The ice water system provides 30.1 kW_{th} at 52°C (Table B.27). Heat recovery from condensation is due to the condensation temperature in comparison to the cold brew water temperature of 17°C not practical for both chiller systems.

Table B.27: Heat recovery potential from hot gas deheating

		space cooling	ice water
Deheating Temperature	T	20°C	21.5°C
Deheating Enthalpy	Δh	34 kJ kg^{-1}	84 kJ kg^{-1}
Maximum Heat Recovery	$\dot{Q}_{hr,th}$	4.3 kW	30.1 kW

The chiller system for ice water supply do not run constantly during the day. Operation time is mainly at night. Loading the water storage is normally between 18.00 o'clock and 5.00 o'clock. Hence, the actual propulsion power of the compressors affects direct the heat recovery. An analysis of the compressors results in five states of operation. As Figure B.14 illustrates, the heat recovery potential varies from 30.1 kW_{th} at 100% (Table B.27) to 6.9 kW_{th} at 25%.

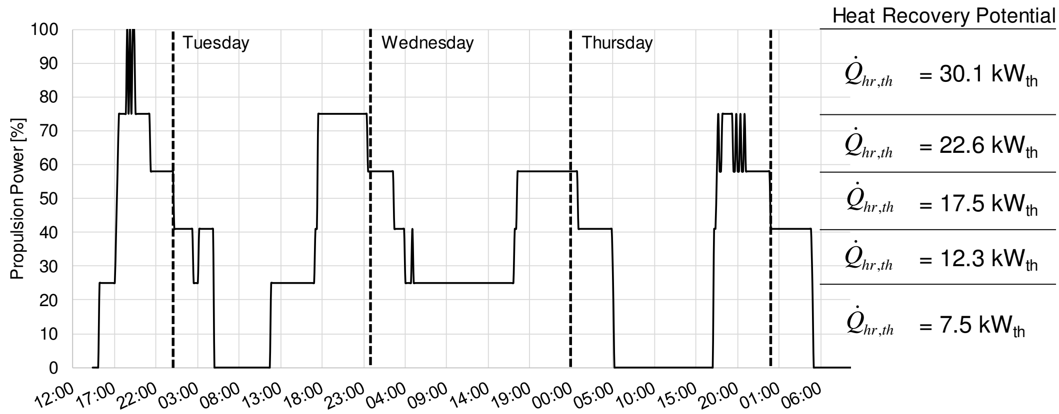


Figure B.14: Propulsion power of compressors ice water supply (21.06 – 25.06.2010)

The definition of a heat recovery factor hrf helps to determine the annual heat recovery energy. With equation (B.1) hrf is 0.215 and based on the proportion of maximum heat recovery and propulsion power. The propulsion energy for the ice water compressors was at 209,000 kWh$_{el}$ in 2010. A transmission efficiency of 0.9 considers transmission losses of heat recovery. Result with equation (B.2) is finally the available heat recovery energy of 40,450 kWh$_{th}$.

$$hrf_{ch} = \frac{\dot{Q}_{hr,th}}{P_{el}} \quad \text{(B.1)}$$

$$hr_{ch,energy} = hrf_{ch} * Q_{el} * \eta_{trans} \quad \text{(B.2)}$$

Two air-cooled compressors provide the compressed air. This is mainly for the filler. The propulsion power reaches about 70 kW$_{el}$ (Figure B.15) and is dominated with filler operation. The basic load of 22 kW$_{el}$ is just for pressurising and compensation of losses.

An air duct system is connected to the compressor housing and can supply waste heat direct for space heating to production halls. Integrating the waste heat into a LGH-supply is with regard a waste heat temperature below 40°C and the air-cooling configuration not useful.

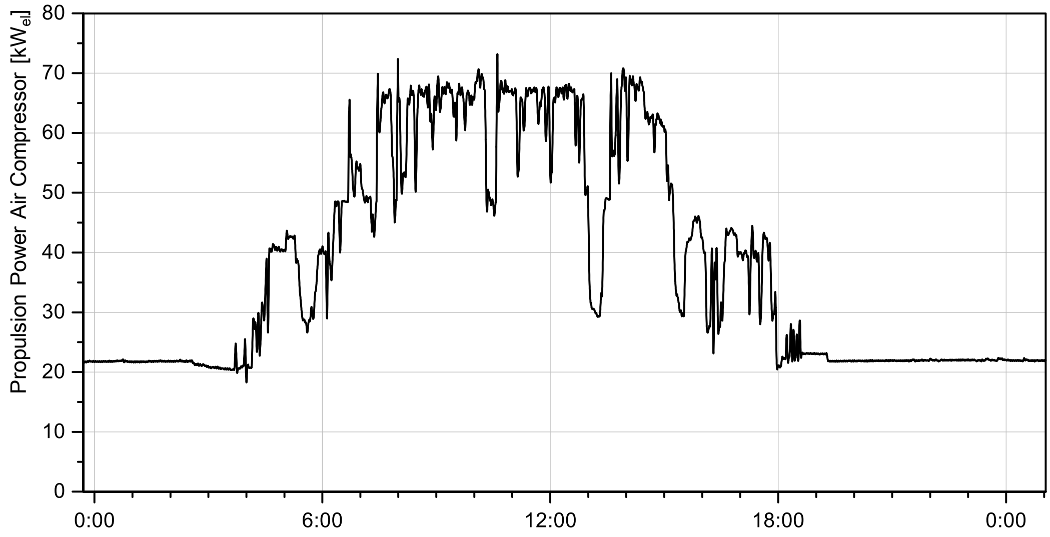


Figure B.15: Propulsion power air compressors (exemplary production day)

Several durations as well as various start and stop times of energy consumers and energy sources require an indirect heat recovery as described with the pinch analysis. In case of the LGH-supply, the drain tank is suitable as energy compensating element. The time event chart (Kemp, 2007) help to verify heat exchange between consumers and heat recovery.

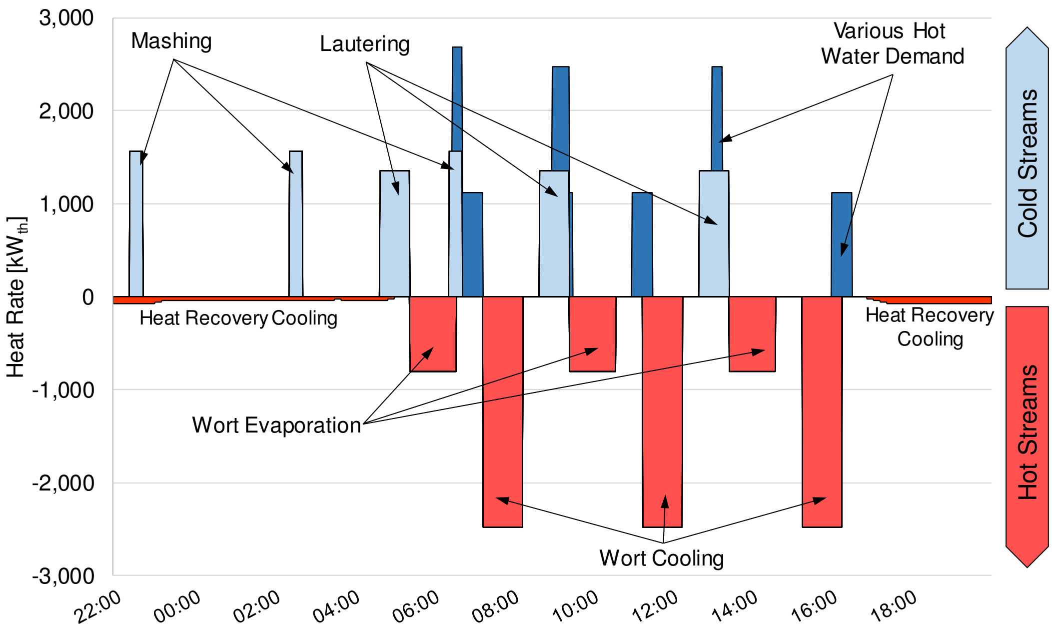


Figure B.16: Time event chart of low-grade heat supply for 3 brews

Figure B.16 shows the analysis of LGH-supply for a production day with three brews. It includes the present cold streams mashing, lautering and various hot water demand as well as the present hot stream wort cooling. Additional the hot streams wort evaporation and heat recovery from ice water cooling system is integrated with the potential defined above.

The drain tank enables to shift the available energy without rescheduling the process sequences. A rescheduling is furthermore limited: each brew runs with a fixed process; multiple use of brew house equipment. The energy balance of the LGH-supply for the production day with three brews show results a surplus of hot streams (Table B.28), illustrated with a heat recovery rate of 101% without storage losses. However, varying production as well as hot water demand leads to many different cases. The time event chart above and the respectively energy balance is only for a specific case. Hence, the applied method gets very complex with the number of cases and is therefore limited.

Table B.28: Energy balance LGH-network for 3 Brews

	Cold streams	Hot streams
Mashing	2,865 kWh_{th}	
Lautering	4,200 kWh_{th}	
How Water	2,895 kWh_{th}	
Wort Evaporation		2,445 kWh_{th}
Wort Cooling		7,155 kWh_{th}
Heat Recovery Cooling		495 kWh_{th}
Total Energy	9,960 kWh_{th}	10,095 kWh_{th}
Heat Recovery Rate	*~ 101%*	

B.6 Energetic optimisation – concept of low-grade heat supply

The supply of hot brew water at a temperature of 84°C remains background for the concept of a LGH-supply. The additional heat sources wort evaporation and heat recovery from cooling complete existing configuration is. Figure B.17 gives an overview of the concept. An existing cold-water drain tank supplies brew water to the system. Three independent stages of heat recovery heat the cold brew water and feed it to the hot water drain tank.

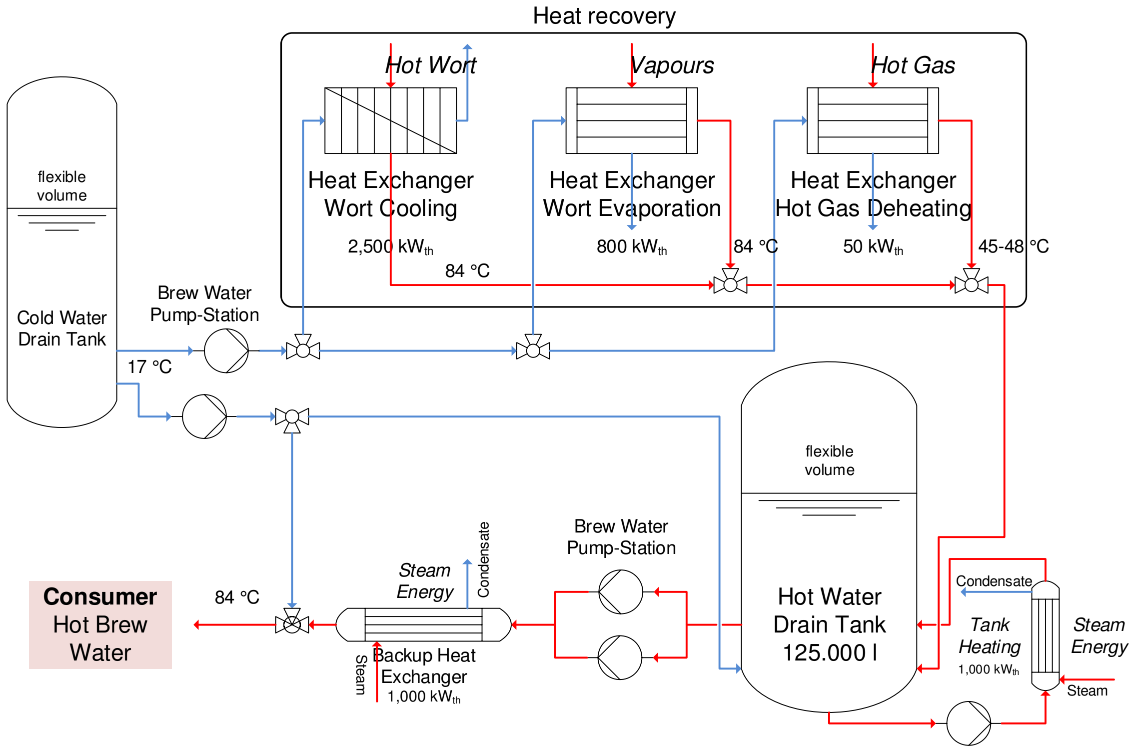


Figure B.17: Concept of LGH-supply for the brewery

A steam energy supply direct to the drain tank completes energy supply with wort cooling, wort evaporation and hot gas deheating from ice water cooling. The steam energy supply ensures the defined temperature in the drain tank and compensates missing hot brew water from heat recovery. A second steam energy supply between hot water drain tank and consumers ensures always the right conditions for the brew water demand. This backup compensates also energy losses from the hot water drain tank.

B.7 Energetic optimisation – energy balance of concept

With analysis, the annual energy demand of the system concept is 2,450 MWh$_{th}$. The energy balance for the defined LGH-supply (Table B.29) shows a heat recovery of 1,410.25 MWh$_{th}$. The remaining steam energy demand is 1,039.75 MWh$_{th}$. Heat recovery has a fraction of 57.6% and the conventional steam energy of more than 30% lower in comparison to the current system configuration.

Table B.29: Energy balance LGH-network concept

	Energy supply	Energy demand
Wort Cooling	1,021 MWh_{th}	
Wort Evaporation	348.8 MWh_{th}	
Hot Gas Deheating	40.45 MWh_{th}	
Steam Energy	1,039.75 MWh_{th}	
Hot Brew Water		2,450 MWh_{th}

B.8 Energetic optimisation – concept evaluation

Existing structures as the LGH-supply provide promising conditions for reconfiguration and optimisation. However, the brewery specific direct use of brew water limits the energy consumers. It is for example not possible to integrate a consumer CIP equipment, bottle cleaning or space heating. These consumers require a LGH-network with a circulating heat transfer medium.

The analysis of heat consumers results many options for a LGH-supply. Further detailed analysis extracted direct consumers of hot brew water. Based on the existing configuration of heat recovery from wort cooling a LGH-supply for hot brew water supply looks most promising. This is background regarding to existing drain tank for hot brew water and integrated heat supply from steam distribution. The technical challenge is the integration of the additional heat recovery from vapour condensation and hot gas deheating of the chiller system. Furthermore, not all waste heat sources supply the required hot brew water temperature and the drain tank with hot brew water causes energy losses. That low temperatures below as well as energy losses from drain tank compensates the connection to the steam distribution. Steam energy ensures also the defined supply temperature to the consumers. Large parts of the existing hot brew water supply can applied within the new design. A reconfiguration of the company structure is not necessary and the concept is technically feasible.

From an energetic point of view, the concept reduces the steam energy demand by 30% (Table B.29). This is a remarkable improvement just with the integration of waste heat. However, the steam energy demand is always at more than

1,000 MWh_{th} a^{-1}. This provides always promising conditions concerning the integration of a SPH-system.

The economic efficiency for this system configuration is just practicable with a rough estimation at this concept level. Large parts of the existing structure remain without or only with small adoption and do not require significant investment. Significant investment however, is necessary for tapping the waste heat sources. This is first for the vapour condensation, because this means an intervention in the production equipment. A detailed analysis is required to calculate the effort. However, this technique is meanwhile standard in lots of breweries an available from all suppliers of brewery equipment (Steinecker, 2012; Gea, 2014).

B.9 Solar process heat system - analysis of roof area

The base area of the production buildings is about 15,300 m². With exclusively flat roofs and southeast orientation of -10°, this is *Roof Area Factor B* of 0.5. The aerial view (Figure B.18) is for the evaluation of the flat roofs with the four criteria.

Figure B.18: Aerial view on production site (Bayernatlas, 2013)

The aerial view shows less substructures on the roofs and almost no shading. There is only building with a large contiguous areas. Results is a *Roof Structure Factor I* of 0.61 and finally a *Usage Factor II* is 0.305 (equation (B.3)). A maximum collector area of 4,660 m² is available.

$$II = 0.5 \times (0.7 \times \frac{4+5+4}{15}) = 0.305 \qquad (B.3)$$

As Figure B.19 illustrates, the available collector mounting area is divided in several sections. Collector mounting area and boiler room belong to the same group of buildings. Installation of most piping is possible inside the building. The heat storage is located near to the boiler. In summary, the structural conditions are advantageous for a SPH-system.

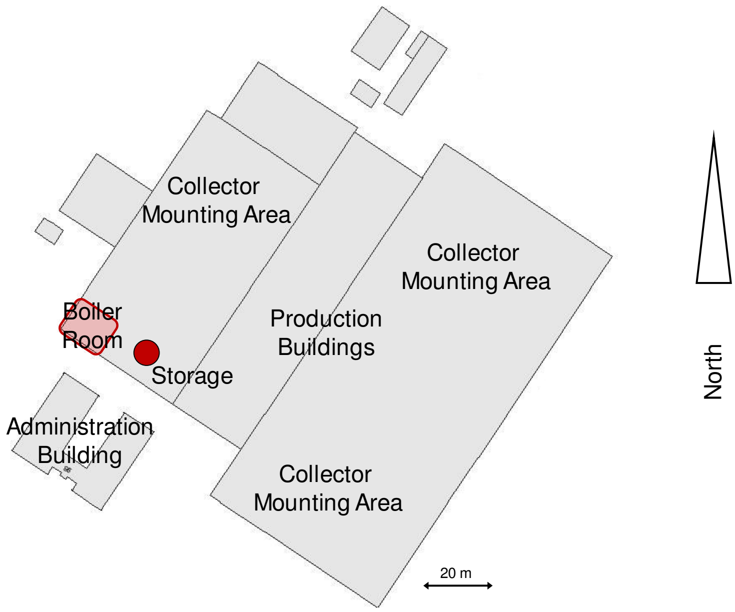


Figure B.19: Layout with collector mounting areas (cf. Bayernatlas, 2013)

B.10Solar process heat system – SPH-system configuration

Initial point for the SPH-system configuration is an existing but unused tank. It is equipped with pipe connection charging and discharging and therefore reconfigured to a heat storage. Table B.30 shows the resulting configuration. The storage volume is further background for the design of the collector area. The orientation of the collector array is adapted to the building conditions. The input parameters for collector and storage circuit are from the general system configuration background in Appendix A. Table B.31 gives the final configuration parameter. That is further input for system modelling and simulation.

Table B.30: Storage configuration

Heat Energy Storage	Volume	$\dot{V}$	120	m^3
	Diameter		4	m
	Heat Loss Coefficient	u	1.2	$W\,m^{-2}\,K^{-1}$
	Connection	stratified charging / discharging		

Table B.31: Configuration parameters of SPH-system

Collector Area	Collector Type	-	Flat-Plate	
	Collector Array	A	1.496	m^2
	Orientation	-	0	°
	Inclination	-	45	°
Collector Circuit	Heat Transfer Medium	-	Water-Glycol-Mixture	
	Volume Flow Rate	$\dot{V}$	25	$l\,h^{-1}\,m^{-2}_{ca}$
Heat Exchanger	Flow Type	-	Counter	
	Constant Heat Transfer	$u_{a,0}$	120	$kW\,K^{-1}$
	Mass Flow hot	$\dot{m}$	10.4	$kg\,s^{-1}$
	Mass Flow cold	$\dot{m}$	9.6	$kg\,s^{-1}$
Storage Charging Circuit	Heat Transfer Medium	-	Water	
	Volume Flow Rate	$\dot{V}$	23	$l\,h^{-1}\,m^{-2}_{ca}$
Piping	Outside	L	320	m
	Inside	L	40	m
	Heat loss Coefficient insulation	UA	0.35	$W\,m^{-2}\,K^{-1}$

B.11 Solar process heat system – reconfiguration of low-grade heat supply

The LGH-supply provides many possibilities for improvement. Several energy sources are able to supply hot brew water with target parameters to the storage or pre-heat cold brew water. This aims to complement wort cooling and substitute steam energy. The analysis of waste heat potentials results wort evaporation and cooling systems as additional energy sources. Finally, the SPH-system can supply process heat. A successive integration of all those energy sources to the conventional system model enables detailed analysis and evaluation of each source. This is always regarding the implementation of the solar-thermal component and gives comprehensive results on the competition of different heat sources but show also the increasing complexity of such a multivalent process heat supply.

Figure B.20 illustrates the final structure of the LGH-supply with all available heat sources. Wort cooling and wort evaporation are able to supply hot brew water at the defined temperature to the storage. Solar and heat recovery cooling need additional steam energy to reach this temperature. Steam energy supplies the remaining brew water not supplied by the other sources. A backup also with steam energy compensates the losses of the drain tank and ensure the requirement on process temperature.

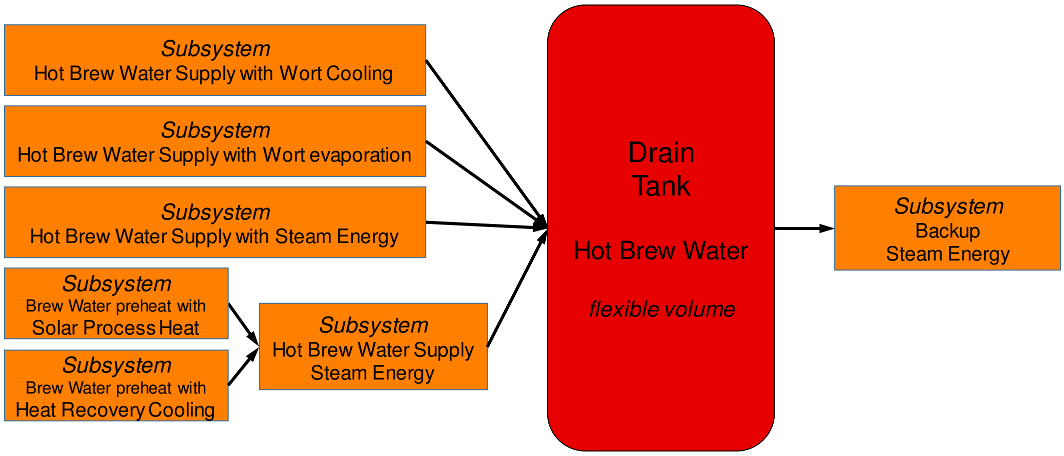


Figure B.20: Subsystem structure of low-grade heat supply with multivalent heat sources

B.12System simulation – simulation of basis system

The simulation starts with the validation of the existing LGH-supply that supplies the hot brew water supply. This means the behaviour of the drain tank, heat recovery from wort cooling and steam energy supply as well as the defined supply temperature of hot brew water.

The energetic analysis provides the simulation parameter and the background for the energy load profiles. These are developed with process data in combination with temporary data acquisition and consist of the elements:

- mass flow,
- flow temperature,
- and return temperature (temperature of cold brew water).

Main load profile for the simulation of the breweries LGH-supply is the hot brew water consumption. It is developed with process parameter on the one side and with temporary data acquisition on the other side. As the cold brew water has a continuous temperature of 17°C and the supply temperature of hot brew water is at 84°C, the development of the load profile focuses on the mass flow. All measurement is individually at each consumer of the hot brew water consumption with a portable clamp on ultrasonic flowmeter.

The first two consumers are processes of the brew house. Each brew includes these two processes with a defined volume flow and duration. Process parameter and the brew house capacity define the hot brew water consumption. Individual measurements validate that brew water consumption. Third consumer is the cleaning. A validation with fixed parameters is not able in this case. Temporary data acquisition at the supply pipe provide the mass flow profile for that consumer.

Figure B.21 shows finally the load profile for an exemplary production week. It represents the breweries complete hot brew water consumption and is developed on combined from temporary measured data and process data. The production programme provide additional input and enable the development of an annual load profile ready for the simulation. The hot brew water consumption enables the validation of the LGH-supply. With continuous temperatures, this is possible exclusively with the load profile of the hot brew water. First approaches is the comparison of the temporary measurements with a simulated hot brew water consumption. Table B.32 shows therefore a deviation of 0.5% from measurement to simulation for an exemplary week. Second approach of the validation is with an annual simulation. It results a brew water consumption of 32,017,000 kg a^{-1}. Compared to brewery data this varies with 3.6% (Table B.33). The validation shows therefore adequate accuracy for the load profile.

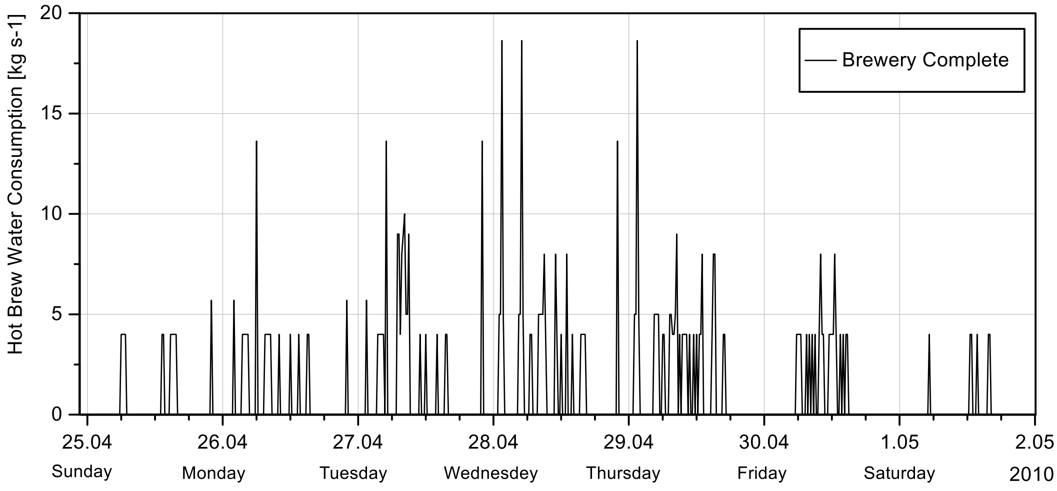


Figure B.21: Exemplary hot brew water consumption

Table B.32: Validation of hot brew water consumption (temporary measurement)

	Measurement	Simulation	Deviation
	kg	kg	%
Exemplary Week	558,310	561,260	0.5

Table B.33: Validation of hot brew water consumption (brewery data)

	Brewery Data	Simulation	Deviation
	kg	kg	%
Annual Consumption	30,900,000	32,017,000	3.6

Table B.34 distinguishes with an energy balance energy from wort cooling and the steam energy direct supplied to brew water and for backup of the model configuration ID con bw. The energy demand of the simulation differs with less than 2% from the energy demand of the data acquisition.

Table B.34: Energy balance low-grade heat supply with Drain Tank

Energy Source		**Brewery (2010)**	**ID con bw**
hr Wort Cooling	MWh_{th}		1,024.9
Steam energy *Brew Water feed*	MWh_{th}		1,383.3
Steam energy *Backup*	MWh_{th}		63.2
Energy Demand	MWh_{th}	2,440	2,471.4

Important for this configuration is fill level the drain tank affected with brew water supply to the tank from heat recovery and steam energy as well as brew water supply to processes. With dropping a fill level of 61% (brewery configuration) of the maximum storage volume, the brew water charging with steam energy starts. That level of 61% provides also enough volume for brew water charging with heat recovery. Figure B.22 illustrates the fill level for an exemplary week.

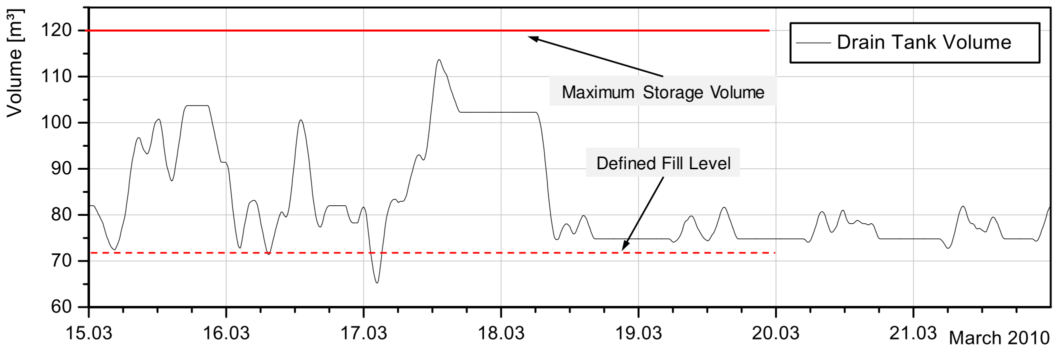


Figure B.22: Fill level of drain tank (from simulation)

The brew water supply with constant heat capacities for heat recovery from wort cooling (2.440 kW_{th}, simulation) and steam energy (800 kW_{th}, simulation) to the storage is from each source at 84°C. With drain tank losses, the temperature of the brew water in the tank drops to of 80–83°C. As Figure B.23 illustrates, the process temperature is finally 84°C.

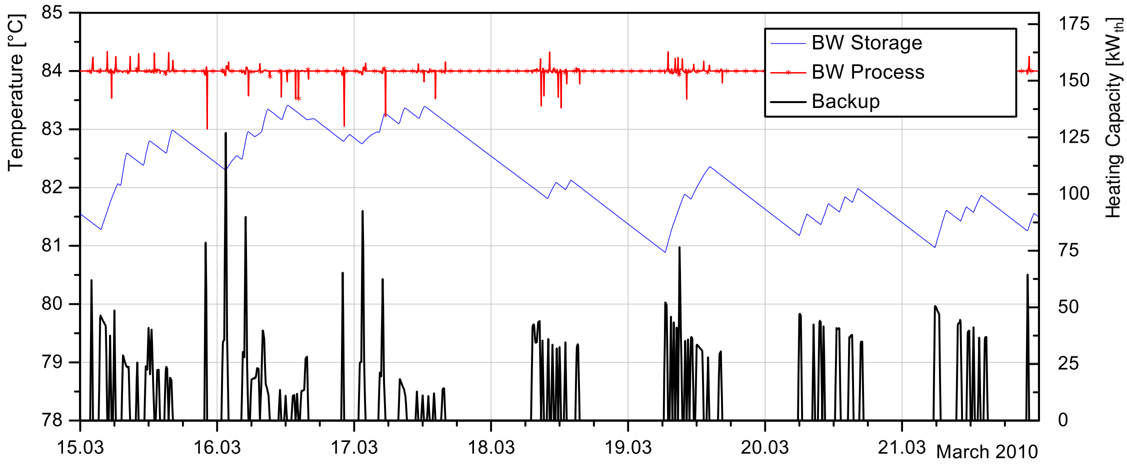


Figure B.23: Temperature of brew water and heating capacity of backup ID con bw

The difference between storage and process temperature compensates a backup with a necessary heat capacity of 150 kW_{th} (Figure B.23). The simulation model with heat source components and drain tank works within the expected parameters and is validated for using within concept optimisation.

B.13 System simulation – simulation of reconfigured variations of LGH-supply

The reconfiguration of this existing LGH-supply (ID con bw) towards sustainability is in several steps, whereas the initial configuration remains. First step is a variation of different heat recovery combinations (ID hr 1, ID hr 2, ID hr 3). Second step is the integration of a sola process heat system ('ID solar bw') without additional heat recovery and enables its individual analysis. Finally, the integration of combined heat recovery and solar process heat (ID solar bw + hr) is the third step. Figure B.24 compares the defined configurations of LGH-supply.

	Variations of Heat Source Configuration					
Model ID	con bw	hr 1	hr 1	hr 3	solar bw	solar bw + hr
Solar-Thermal Energy					●	●
hr Wort Cooling	●	●	●	●	●	●
hr Wort evaporation		●		●		●
hr Cooling System			●	●		●
Steam Energy before storage	●	●	●	●	●	●
Backup (Steam Energy) after storage	●	●	●	●	●	●

Figure B.24: Source configurations of LGH-supply with heat recovery *hr* and solar process heat *solar*

That procedure aims to figure out competing heat sources and avoid negative influence of heat sources on each other. All the sources heat up the brew water individually and charge it to the drain tank. This simplifies the heat source priority.

The SPH-system however, is just active to fill brew water demand that is not available with heat recovery. A final restricting factor is the tank volume and responsible for switch off all brew water supply to the tank.

Table B.35 compares the energy balance of the conventional configuration (ID con bw) with the heat recovery configurations (ID hr 1, ID hr 2, ID hr 3). Focus is on heat recovery sources and steam energy. A full integration of heat recovery 'hr 3' results in a steam energy reduction of 30%, whereas the proportion of heat recovery reaches about 59% of the total energy demand. Dependences of heat recovery source do not occur.

Table B.35: Energy balance of LGH-system variations with heat recovery

Energy Source		**ID con bw**	**ID hr 1**	**ID hr 2**	**ID hr 3**
hr Wort Cooling	MWh_{th}	1,024.9	1,018.7	1,024.3	1,014.7
hr Wort Evaporation	MWh_{th}	---	362.5	---	362.4
hr Cooling Chiller	MWh_{th}	---	---	68.0	68.2
hr Total	MWh_{th}	1,024.9	1,381.2	1,092.3	1,445.3
Steam energy *Brew Water feed*	MWh_{th}	1,383.3	1,025.5	1,316.7	962.5
Steam energy *Backup*	MWh_{th}	63.2	51.4	67.0	55.5
Energy Demand Hot Brew Water	MWh_{th}	2,471.4	2,458.1	2,476.0	2,463.3

The integration of waste heat from wort evaporation and cooling requires a reduction of the defined fill level of the tank from 61% to 42%. Simultaneous operation of waste heat sources would otherwise fill up the tank to the maximum volume and cut down heat recovery. Reducing the fill level keeps the storage volume below the maximum (Figure B.25).

The analysis of the storage and process temperature as well as the heat capacity of backup for the configuration hr 3 (Figure B.26) shows comparable results to configuration ID con bw. Brew water supply with steam energy is again at 800 kW_{th}. Hence, less operation time causes the lower steam energy demand.

Backup compensates the temperature losses and ensures the required brew water temperature (BW Process) with a heat capacity of maximum 100 kW_{th}. This is also for the configurations ID hr 2 and ID hr 3.

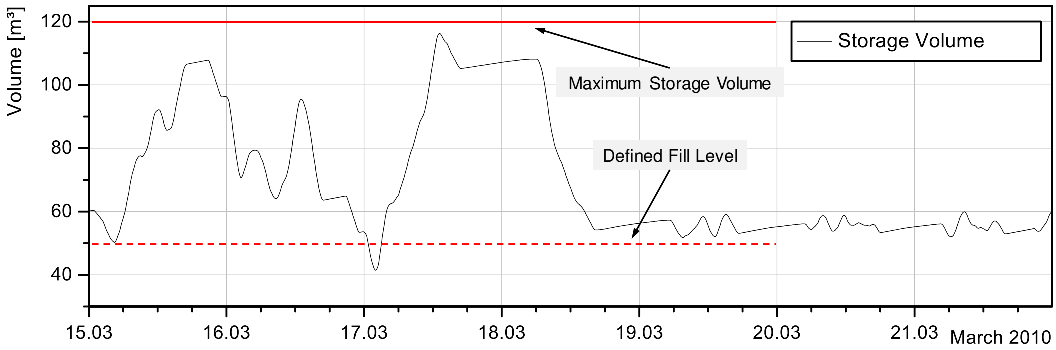


Figure B.25: Fill level of drain tank with reduced fill level ('hr 3')

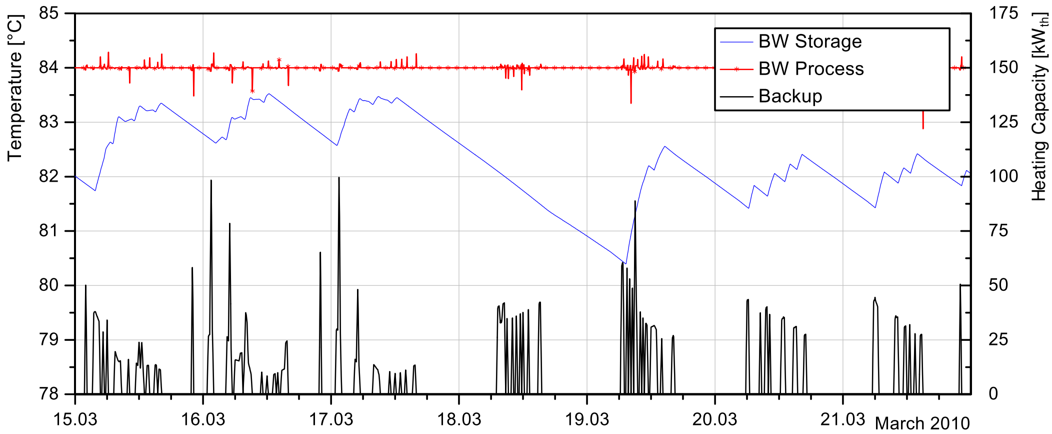


Figure B.26: Temperature of brew water and heating capacity of backup ID hr 3

Full heat recovery from wort cooling, wort evaporation and cooling as well as solar process heat is the final system configuration ID solar bw + hr. Table B.36 compares it with the configurations ID con bw and ID solar bw. As one might expect shows ID solar bw + hr with 459.7 MWh_{th} a^{-1} the lowest steam energy demand of all system configurations. This is about 67% less than for the configuration ID con bw. About 59% of the system energy demand is from heat recovery and more than 20% is solar process heat.

A major result of the comparative analysis of ID solar bw and ID solar bw + hr is furthermore the disadvantage influence of heat recovery on the solar process heat source (Table B.36). Configuration ID solar bw + hr supplies therefore 22% less solar energy to process than ID solar bw. This finding clarifies the direct correlation of prior heat recovery and subordinate solar process heat. A reduced energy supply to causes higher storage temperatures in the solar thermal system and has unfavourable effects on the energy losses.

Table B.36: Energy balance LGH-supply with heat recovery and SPH-system

Energy Source		**ID con bw**	**ID solar bw**	**ID solar bw + hr**
Solar Energy from *collector area*	MWh_{th}	---	704.5	576.5
Energy losses from *storage and piping*	MWh_{th}	---	58.8	73.3
Solar Energy to *Process*	MWh_{th}	---	645.6	503.2
hr Wort Cooling	MWh_{th}	1,024.9	1,024.2	1,014,8
hr Wort Evaporation	MWh_{th}	---	---	362,4
hr Cooling Chiller	MWh_{th}	---	---	68.2
hr Total	MWh_{th}	1,024.9	1,024.2	1,445.4
Steam energy *Brew Water feed*	MWh_{th}	1,383.3	739.7	459.7
Steam energy *Backup*	MWh_{th}	63.2	64.3	56.3
Energy Demand Hot Brew Water	MWh_{th}	2,471.4	2,473.8	2,464.6

Providing hot brew water at 84°C is the main objective and control strategy of the SPH-system. However, the defined process temperature is just reached for some short periods. As Figure B.27 illustrates, the temperature of solar preheated brew water fluctuates between 40–84°C. Hence, the system needs always support from steam energy supply to ensure the parameters of hot brew water and cannot be a unique heat supply system in this connection.

About 65% of the annual solar process heat supply is from April to September (Figure B.28). Solar process heat provides proportionality better yields from October to March. This is a result of the return temperature to the SPH-system with cold brew water at 17°C. It illustrates the advantage of 'cold' return flow in contrast to the high return temperature of the LGH-network at the dairy.

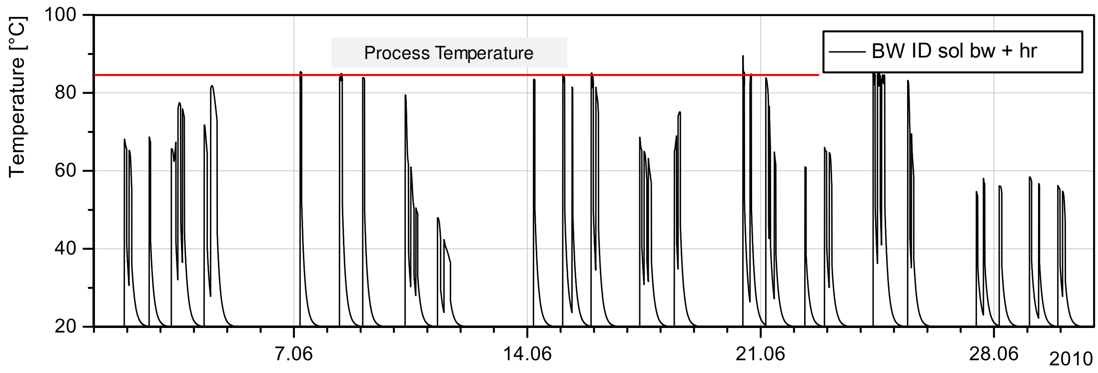


Figure B.27: Temperature of solar preheated brew water (ID solar bw + hr)

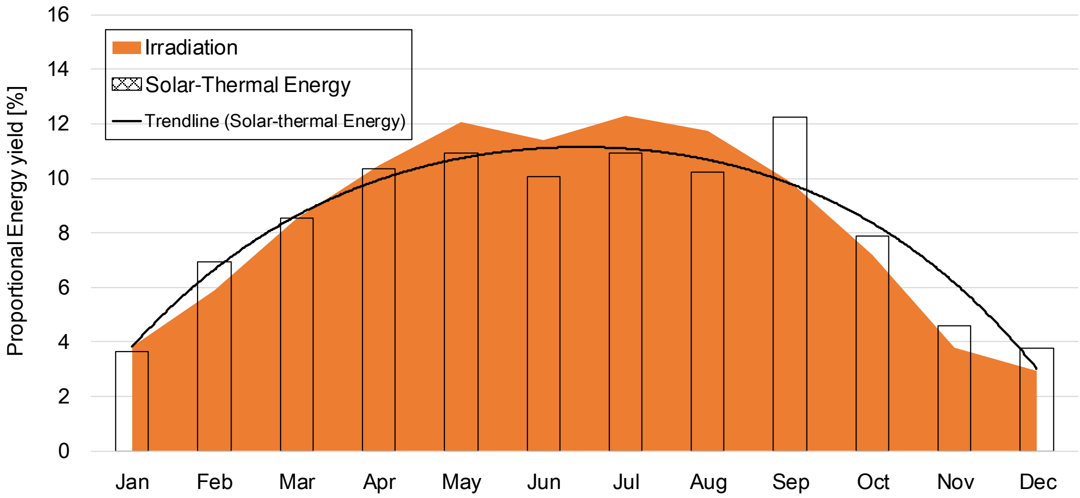


Figure B.28: Proportional solar energy of configuration ID solar bw + hr (2010)

The evaluation of specific heat capacities completes the energetic system evaluation. Equation (B.4) defines the necessary utilisation factor. This is applied for specific heat capacity of the collector array UF_{col} and specific heat capacity of the solar process heat supply to LGH UF_{supp}.

$$UF = \frac{Specific\,Heat\,Capacity}{Global\,Radiation} \qquad (B.4)$$

Defined load cases are background for a system analysis. Four typical days (TD) represent this load cases with the global radiation on the inclined collector surface:

- TD 1: global radiation > 1.000 W m^{-2}
- TD 2: global radiation ~ 750 W m^{-2}
- TD 3: global radiation ~ 550 W m^{-2}
- TD 4: global radiation < 400 W m^{-2}

UF_{col} is between 0.30 and 0.54 and UF_{supp} is between 0.23 and 0.61 (Table B.37). Between 22–61% of the available global radiation can be used for solar process heat supply (TD 4). This is higher than for the dairy system and confirms the more favourable conditions of low return temperatures.

Table B.37: TD evaluation of system configuration 'ID solar bw + st'

Maximal		**TD 1**	**TD 2**	**TD 3**	**TD 4**
Global Radiation	W m^{-2}	1,095	750	545	345
Specific Heat Capacity *Collector Array*	W m_{ca}^{-2}	565	390	295	105
	UF_{col}	0.52	0.52	0.54	0.30
Specific Heat Capacity *Solar process heat*	W m_{ca}^{-2}	455	170	190	210
	UF_{supp}	0.42	0.23	0.35	0.61

Figure B.29 show exemplary for TD 3 the global radition and the heat capacities for exemplary. As the volume flow is constant and and the return tempertaure stay the same at 17°C, the specic heat capacity is nearly constant. The effect of time shifted use of solar process heat is the same as at the dairy system.

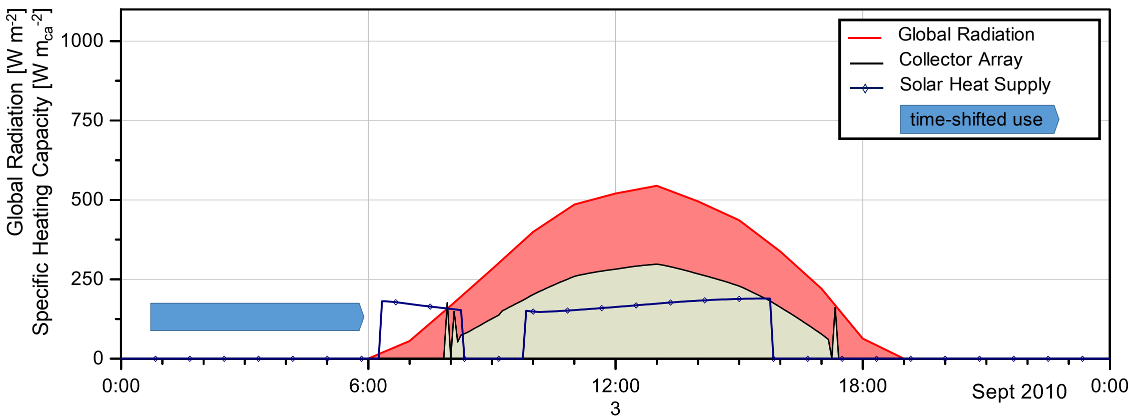


Figure B.29: Global radiation and specific heat capacity TD 3 (ID solar bw + st)

The specific collector earnings (Table B.38) are background for a further energetic and finally economic evaluation of the SPH-system. More significant is the specific collector earning based on the actual solar process heat supply. This is at 431.2 $kWh_{th}\ m^{-2}\ a^{-1}$ for ID solar bw as well as 336.3 $kWh_{th}\ m^{-2}\ a^{-1}$ for ID solar bw + hr. Regarding system location in connection with operation conditions, this are acceptable results.

Table B.38: Specific collector earning of the SPH-systems

Reference Value		**ID solar bw**	**ID solar bw + hr**
Energy of Collector Array	$kWh_{th}\ m^{-2}\ a^{-1}$	469.5	385.3
Solar Process Heat	$kWh_{th}\ m^{-2}\ a^{-1}$	431.2	336.3

The system evaluation aims to define an overall efficiency of the SPH-system. Starting point for the efficiency analysis (Table B.39) is the energy of collector array. The solar efficiency SOL_{eff} reaches 91.6% for ID solar bw and 87.3% for ID solar bw + hr. The irradiation in Table B.39 illustrates additionally the proportion of used solar radiation by the collector array.

Table B.39: Efficiency of solar process heat system

Energy Source		**ID solar bw**	**ID solar bw + hr**
Irradiation on Collector Array	%	267.0	326.3
Energy of Collector Array	%	100.0	100.0
Solar Energy to *Storage*	%	97.6	96.7
Solar Energy to *Process* SOL_{eff}	%	91.6	87.3

The system simulation shows promising results for some configurations with solar process heat. This is first for those with the character of a heat supply network.

Appendix C Dairy case study

C.1 Energetic analysis – energy balance

A steam distribution network is main source for process heat. Fossil fuel-fired steam boiler supply until 2009 the steam energy. A biomass-fired power plant replaced in 2009 the steam boiler. Electricity is used, to operate chiller systems, air compressors and many other applications. The dairy has a comprehensive data acquisition based on an EMS. This is for company energy data but also for more detailed network and process data.

Figure C.1 shows *Balance Area I*, which will be used to analyse the energy supply of the complete dairy plant. This supply includes the steam supplied by biomass and fossil fuels as well as electricity.

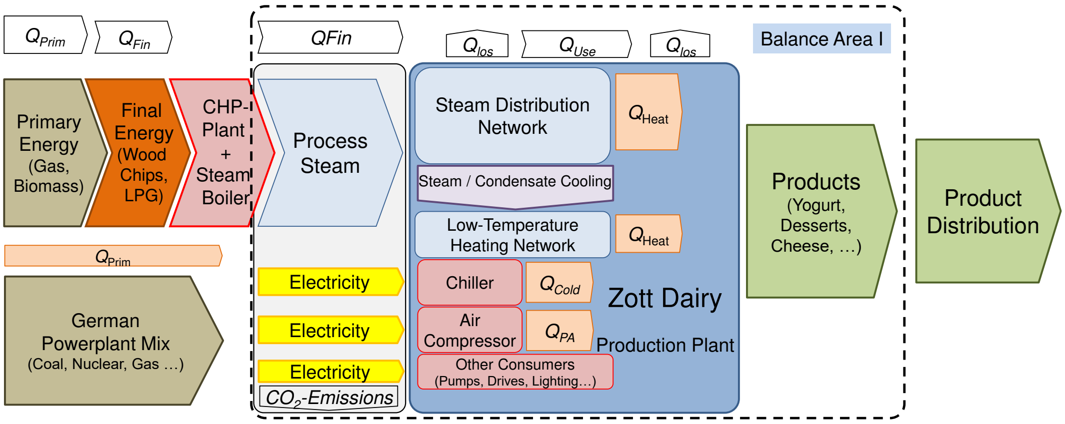


Figure C.1: Definition of balance area I

The definition of characteristics and GHG-emissions for fuels and electricity used for the energy supply are the same as for the brewery and taken from Table B.3.

Since 2009, the biomass-fired power plant with an additional gas-fired peak load steam boiler supplies the dairy with steam energy. The dairy steam boilers are only in operation during standby of the biomass plant. Hence, the primary energy sources of biomass and fossil fuels are only considered in connection with GHG-emissions. These include the emissions of fossil fuels used for steam boiler and the fuels used at the CHP-Plant as well as the emissions for electricity. In contrasts to steam energy, process heat represents the total process heat demand including heat recovery. These data are available since 2009. Table C.1 shows the energy and emission balance for 2008–2011.

Table C.1: Energy consumption and GHG-emissions

		2008	2009	2010	2011
Gas*	[MWh]	64,500	48,246	-	-
Heating Oil*	[MWh]	-	6,927	703	1,038
Steam CHP-Plant	[MWh_{th}]	-	8,278	61,355	62,039
Steam Energy	[MWh_{th}]	55,875	56,940	61,975	62,955
Process Heat	[MWh_{th}]	-	60,490	69,681	70,679
Electricity	[MWh_{el}]	47,565	48,101	51,752	49,888
GHG-Emissions	[to_{CO2Equ}]	43,849	42,693	36,814	36,936

* used only for dairy steam boilers

Because the dairy produces a wide range of products and it is difficult to assign exact energy demands to single products, the basis for the definition of specific key figures is chosen to be the annual amount of milk processed (Table C.2).

Table C.2: Annual milk processing volume

		2008	2009	2010	2011
Milk	[l]	368,390,000	383,332,000	450,161,000	448,715,000
Milk	[t]	358,358	372,891	437,900	436,493

For a benchmark of specific energy demands of other dairies, key figures for process heat and electricity are necessary. Table C.3 shows the figures for the total energy demand, as well as GHG-emissions, expressed on a “per unit of processed milk” basis.

Table C.3: Specific key figures for milk processing

		2008	2009	2010	2011
Process Heat	[$kWh_{th}\ l_{Milk}^{-1}$]	-	0.158	0.155	0.158
Electricity	[$kWh_{el}\ l_{Milk}^{-1}$]	0.129	0.126	0.115	0.111
GHG-Emissions	[$g_{CO2Equ}\ l_{Milk}^{-1}$]	119	111.4	81.8	82.3

The EnergieAgentur.NRW (2012) provide specific key figures for the industrial sector of German dairies. This includes all kinds of dairies (company size and product portfolio) and is therefore given as range. Table C.4 compares the dairy with these figures and gives a deviation to the upper limit of the benchmark.

Table C.4: Benchmark of key figures (EnergieAgentur.NRW, 2012)

		German Dairies	Dairy	Deviation
Process Heat	[$kWh_{th}\ l_{Milk}^{-1}$]	0.02–0.18	0.158	- 12%
Electricity	[$kWh_{el}\ l_{Milk}^{-1}$]	0.01–0.13	0.111	- 15%

The reconfiguring of the steam supply as described, effects the specific GHG-emissions considerably. However, about 30% of the steam supply of the biomass CHP-Plant is based on gas, and gas is also used for maintenance of the company's own steam boilers. The specific emission fell from 111.4 to 81.8 $g_{CO2Equ}\ l_{milk}^{-1}$. Figure C.2 shows the specific process heat demand on a constant level, while the milk processing volume increased clear in 2010. The specific electricity demand decreases slightly but continuous.

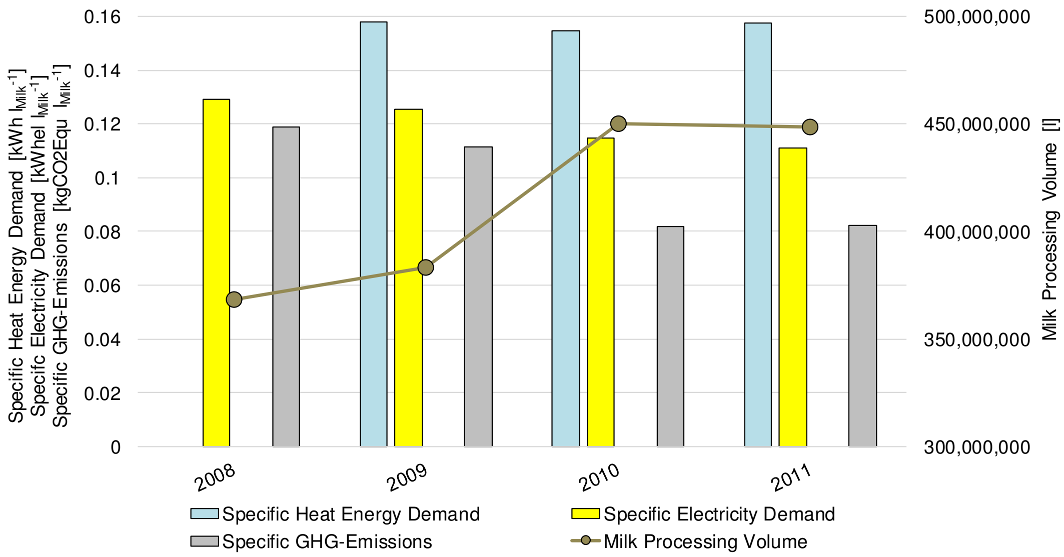


Figure C.2: Development of specific key figures

C.2 Energetic analysis – Energy distribution networks

The dairy runs four distribution networks for thermal energy. This is steam distribution, a LGH-network and two cooling networks. Additionally air compressors supply pressurised air.

The steam distribution network supplies 62,921 MWh_{th} a^{-1} (2011) and is main heat source for all processes and applications (Table C.5). It provides a high temperature and heating capacity covering all heat requirements.

Table C.5: Steam distribution network

Energy Generation	Heat Transfer Medium	Temperature Level	Process Heat
Power Plant + Steam Boiler	Steam	198°C	62,921 MWh_{th} a^{-1}

The LGH-network (Table C.6) as additional heat distribution network supplies 6,868 MWh_{th} a^{-1} (2011). In contrast to the LGH-supply at the brewery, this is a network with water as circulating heat transfer medium.

Table C.6: Low-grade heat network

Energy Generation	Heat Transfer Medium	Temperature Level	Process Heat
Heat Recovery + Steam Boiler	Water	65°C	6,868 MWh_{th} a^{-1}

Table C.7 shows the electricity consuming networks for cooling and pressurised air. The chiller provide with a propulsion energy of 5,708 MWh_{el} a^{-1} (2011) about 21,366 MWh_{th} a^{-1} of cooling energy. The air compressors need 5,567 MWh_{el} a^{-1}. This is further input for optimisation and heat recovery.

Table C.7: Cooling distribution and pressurised air

Energy Generation	Heat Transfer Medium	Temperature Level	Propulsion Energy
Chillers	Ice Water	0–1°C	2,573 MWh_{el} a^{-1}
Chillers	NH_3	-3°C	3,135 MWh_{el} a^{-1}
Compressor	Air	-	5,567 MWh_{el} a^{-1}

The initial situation is something different from that at the brewery. As described, the dairy covers its process heat demand mainly via the steam distribution network. The LGH-network configuration is for processes and applications with lower temperature levels. Table C.8 shows this exemplary with some processes.

Table C.8: Energy distribution networks and energy consumer

	Supply Temperature	Processes	Process Temperature Levels
Steam Network	198°C	UHT Processing	135–150°C
		Pasteurising	72–75°C
LGH Network	65°C	Yogurt Heater (Level 1)	<60°C
		CIP (Acid preheating)	~ 65°C
		Hot Water	45°C

With the LGH-network, the dairy offers a specific initial situation and favourable conditions with regard to various low-temperature process heat sources. Underlining the importance of that network, a second balance area will be defined for the energetic analysis. Figure C.3 illustrates the LGH network in relationship to balance area I. As the figure illustrates, the network is fully integrated into the dairy.

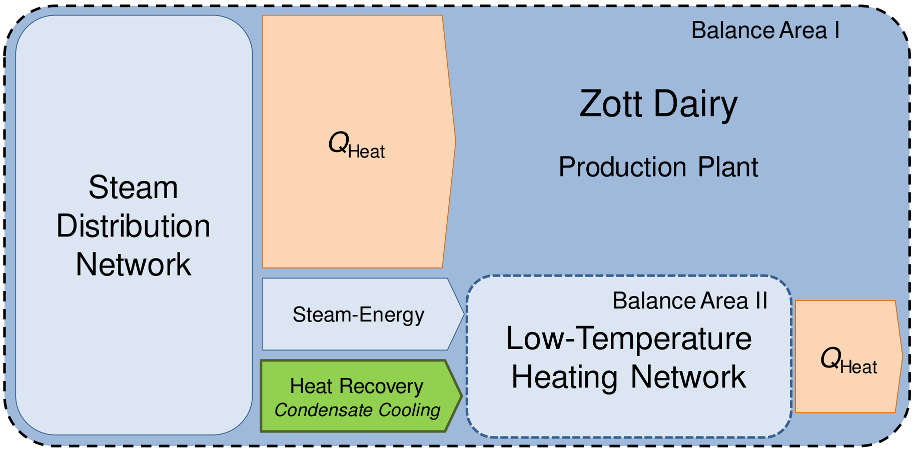


Figure C.3: Definition of balance area II

Condensate cooling and steam provide energy for the LGH network and supply production processes, CIP-facility, hot water preparation and space heating (referred to as LGH heat sinks). The energy supply to the LGH network is serial. First stage is the condensate cooling and dependents on the available condensate volume. The second stage is the steam energy. An important aspect is the existing buffer storage tank with a volume of 160,000 l. It was originally implemented for waste heat use of meantime decommissioned CHP-Units and is currently not in use. This storage tank offers suitable conditions for solar-thermal applications.

The initial purpose of the LGH network configuration today is reducing the temperature of the condensate from the dairy's steam distribution network as it returns to the biomass CHP-Plant. The energy from condensate cooling covers about half of the total network energy (Table C.9) and varies between 240–330 MWh_{th} (2010) and 275–305 (2011) MWh_{th} per month. The steam distribution network supplies the remaining energy. This is necessary for the network operation and can be identified as an important target figure to be covered by waste heat recovery or solar process heat. In contrast to the condensate energy, this is not as constant and varies between 180–640 MWh_{th} (2010) and 160–570 (2011) MWh_{th} per month.

Table C.9: Energy balance for LGH network

		2010	2011
Total	[MWh_{th}]	7,248	6,868
Heat Recovery from	[MWh_{th}]	3,344	3,387
Condensate Energy	[%]	46.1	49.3
Energy from	[MWh_{th}]	3,904	3,481
Steam Distribution	[%]	53.9	50.7

As Figure C.4 illustrates, energy supply to space heating is the most influencing aspect for the characteristic of the LGH network load profile. While the energy supply to CIP, production, and hot water has an average base load of 420 MWh_{th} (May–August), space heating leads to an energy demand of 930 MWh_{th} in winter. Figure C.4 also illustrates the energy supply to the LGH network with the typical monthly progress of steam energy and heat recovery from condensate cooling.

The energetic analysis of the LGH network focuses on the aspects that are important for heat recovery measures (e.g. waste heat from air compressors or chillers) and solar process heat integration. This means the analysis of flow and return temperature, load profiles and the steam energy supply. The process control system provides therefore comprehensive data input.

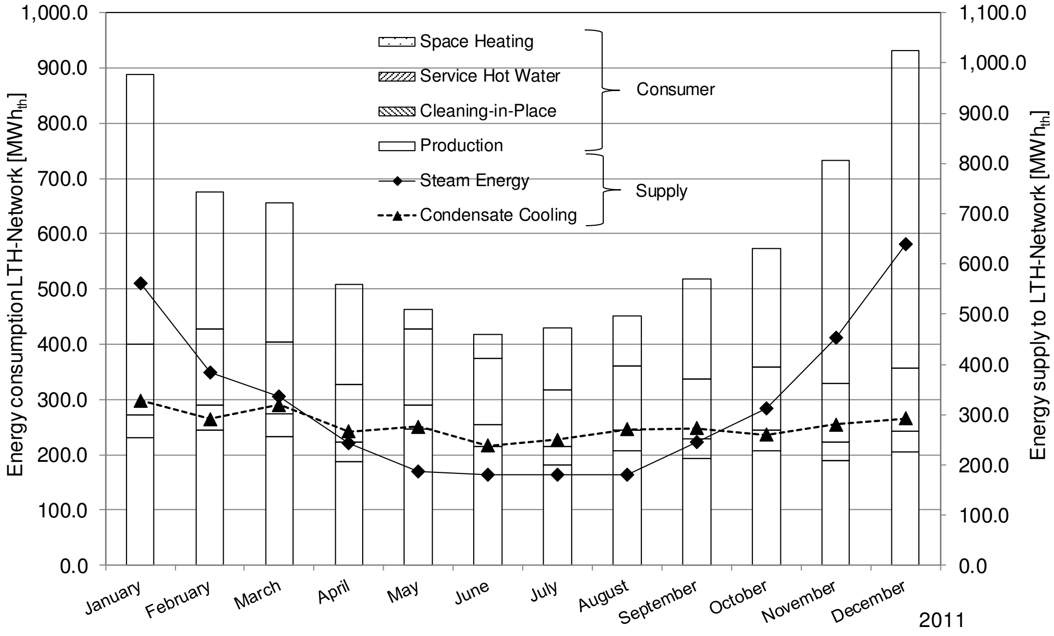


Figure C.4: Annual load profile of LGH-network

Flow and Return Temperature

The flow temperature (Figure C.5) is defined at 65°C and well adjusted to energy supply for the heat sinks.

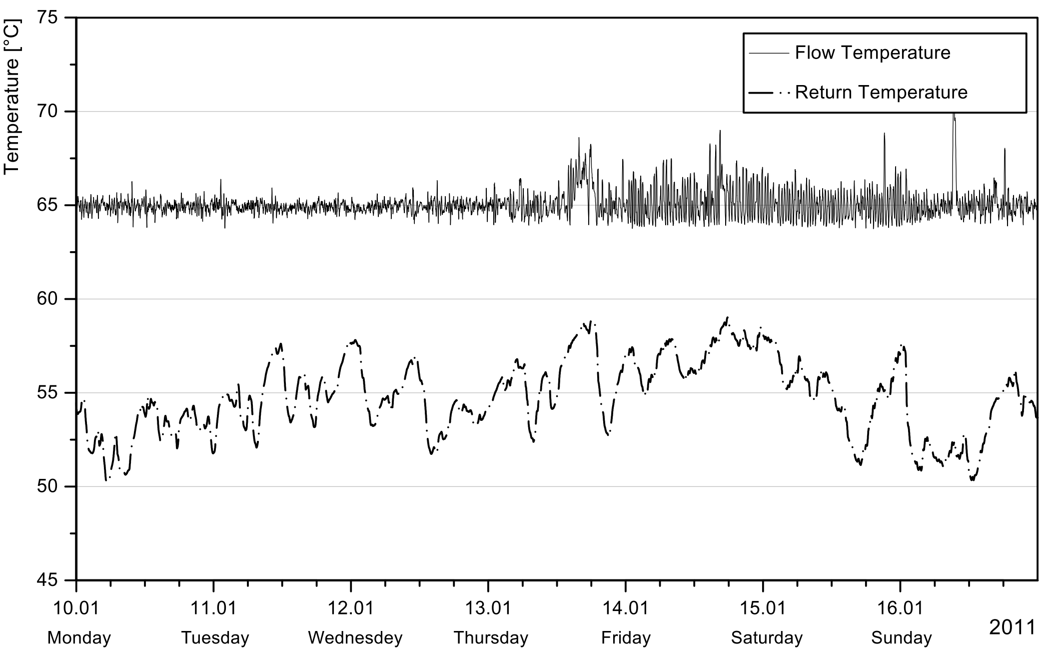


Figure C.5: Exemplary temperatures of LGH-network

This temperature level is stable during regular production from Monday to Friday and gets a little unsteady on weekend, where production and energy demand decreases as Figure C.5 illustrates. Once a month the flow temperature is at 70°C for a period of 3 days. This is necessary for hot water legionella disinfection. The average return temperature is at 55°C, but fluctuation unsteady between 45–62°C. There is no influence of one specific heat sink identifiable.

Load Profile

Figure C.6 show exemplary load profiles of the LGH-network for a week. The difference between the heating capacity of condensate and the total heating capacity of the LGH-network represents the steam heating capacity. The falling energy demand seen on Friday is typical of the LGH network and grows again from Sunday to Monday. This pattern (trend line in Figure C.6 and Figure C.7) is also representative for the energy demand (both process heat and electricity) of the whole dairy and follows the production workload.

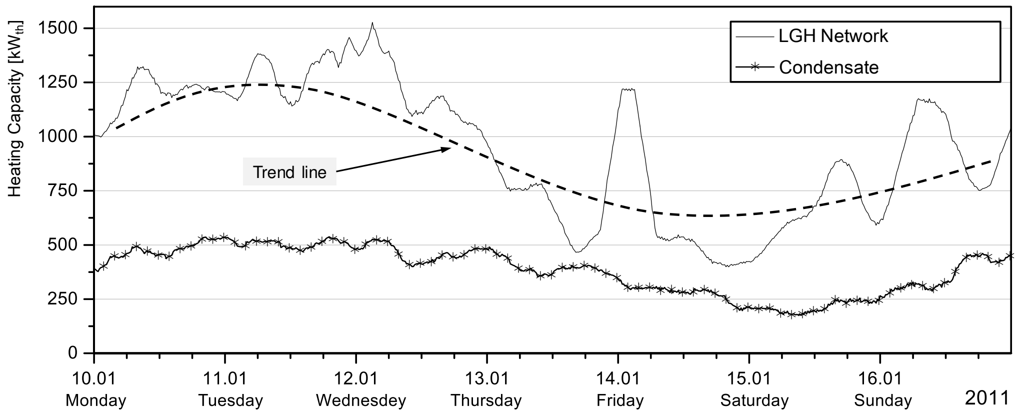


Figure C.6: Exemplary weekly load profiles for LGH-network in winter

The heating capacity of the LGH network in summer is far below 1,000 kW_{th} and reaches for the exemplary week about 820 kW_{th} (Figure C.6). Because of space heating, the heating capacity in winter is much higher and reaches a short peak of 2,500 kW_{th} at the end of January 2011. Normally, the heating capacity is below 1,600 kW_{th} (Figure C.8).

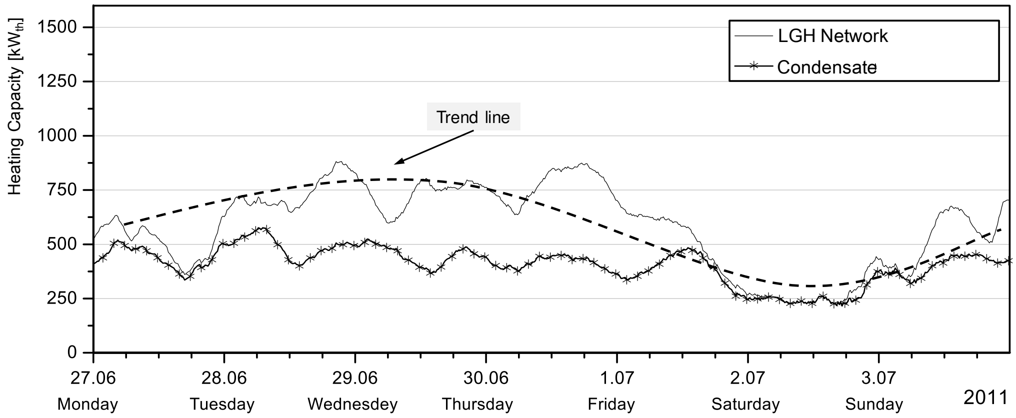


Figure C.7: Exemplary weekly load profiles for LGH-network in summer

As the heating capacity of the condensate is comparable in winter and in summer with a maximum of 610 kW, the steam energy compensates the difference.

Steam Energy Demand

The cooling of condensate as heat recovery has priority and remains the primary energy source of the LGH network. In focus of optimisation is therefore the steam energy. As described before this is about half of the total LGH network energy and is very unsteady. The LGH network needs a steam heating capacity of about 1,000 kW_{th} for regular operation in winter (red frame in Figure C.8). In summer, there is sometimes no steam heating capacity necessary (red frame in Figure C.9).

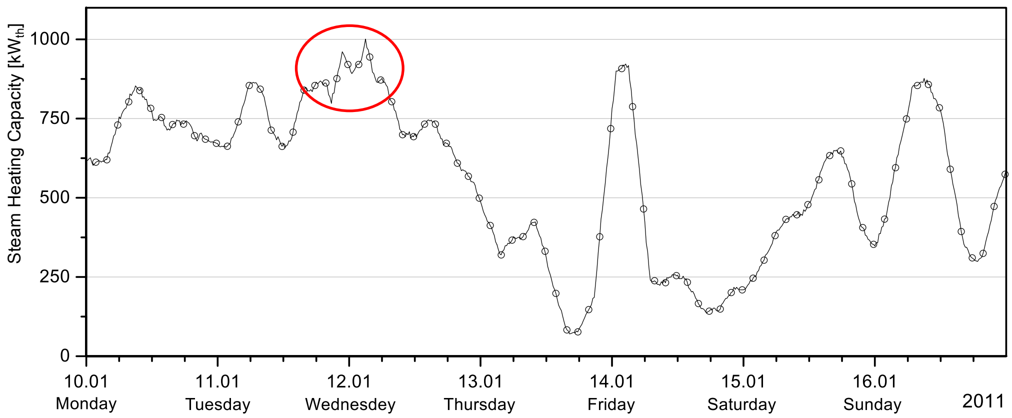


Figure C.8: Exemplary steam heating capacity LGH-network in winter

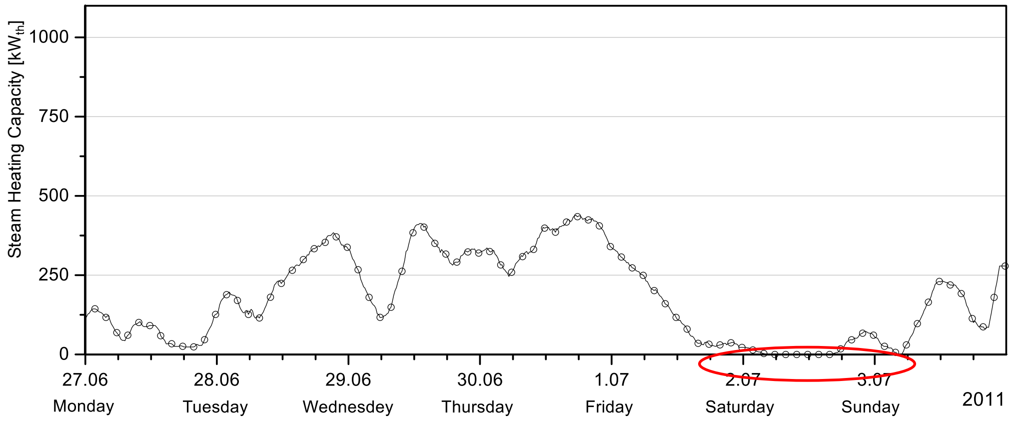


Figure C.9: Exemplary steam heating capacity LGH-network in summer

Figure C.10 and Figure C.11 compare the daily steam energy demand for two exemplary months. When space heating works, the steam energy demand is at 15,000 kWh_{th} d^{-1} and above during regular production (upper chart Figure C.10). Without space heating, the daily steam energy demand is much lower. From Monday to Friday, it varies between 5,000 kWh_{th} and 10,000 kWh_{th} and even disappears sometimes on weekend (04.06.2011 lower chart Figure C.10). However, this are exceptions and the steam energy demand on weekend days is about 2,000 and 4,000 kWh_{th} d^{-1}.

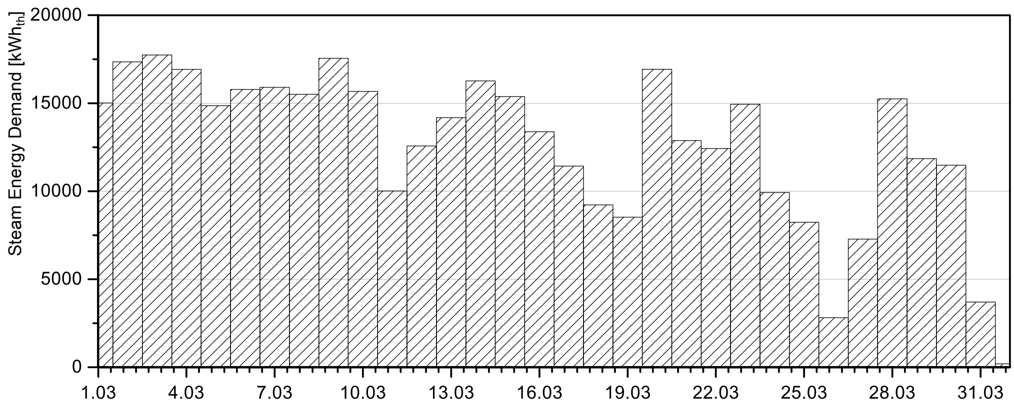


Figure C.10: Steam energy demand LGH-network (space heating period)

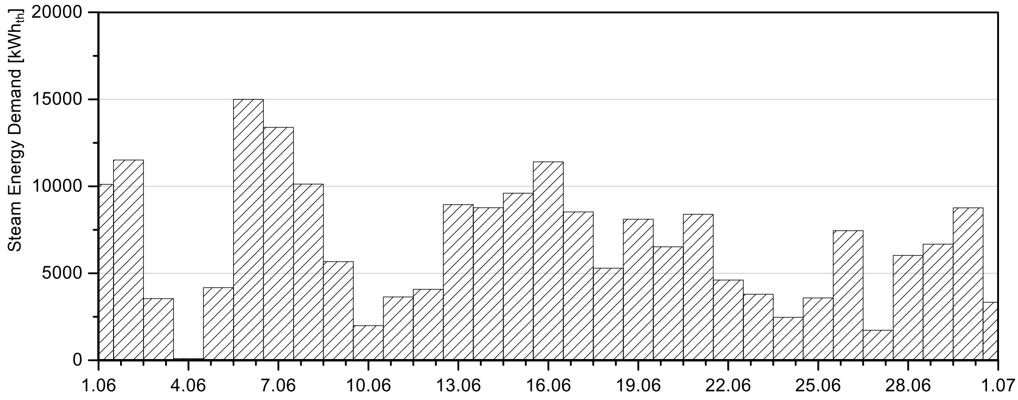


Figure C.11: Steam energy demand LGH-network (outside space heating period)

In summary, the LGH network provides good conditions for waste heat recovery measures and solar process heat:

- *Flow Temperature*
  65°C, favourable for solar-thermal applications
- *Return Temperature*
  55°C on average with a range of 45–62°C, not ideal but quite acceptable
- *Steam Energy (to be substituted)*
  Needed nearly every day for energy supply
- *LGH Network Configuration*
  Existing buffer storage tank (with adequate 160,000 l volume), several heat sinks, expansion technically feasible

C.3 Energetic analysis – brewery sections

A dairy is more complex from a production-related point of view than a brewery. This is due to the higher variety of products and depends on the dairy-specific product portfolio. However, a dairy can also be simplified and divided into five main sections (Figure C.12). The first three and the last sections are comparable in each dairy, with only the fourth product step being different, depending upon the product portfolio. Most distinctions are in the product processing and finishing section, where each type of milk product requires different treatments.

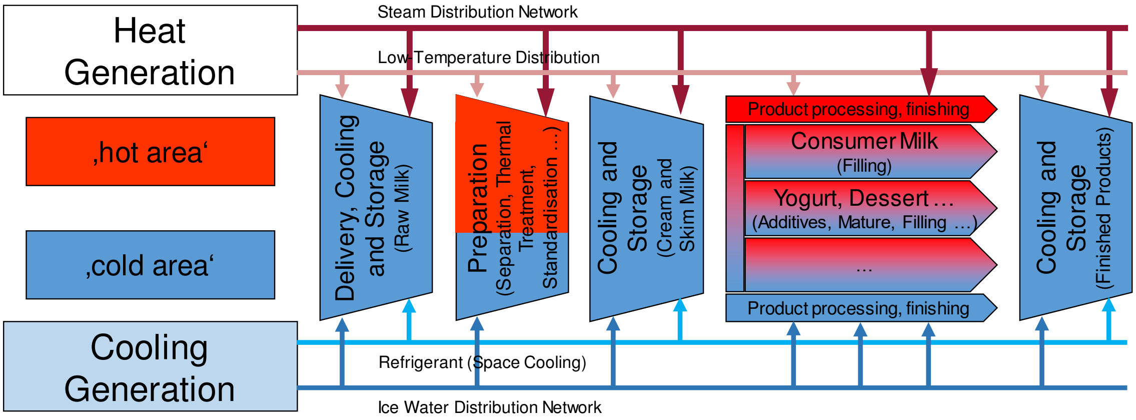


Figure C.12: Dairy production sections and energy supply

Delivery, Cooling, and Storage

Refrigerator trucks collect the raw milk at the producers' farms and deliver it to the dairy. Before further treatment can occur, the pre-cooled milk must be stored and cooled down to a defined level (Table C.10).

Table C.10: Process temperature for delivery, cooling and storage*

	Min. Temperature	Max. Temperature
Process Heat	-	-
Cooling	-	4°C

*(cf. Foissy, 2005)

Preparation

Several processing steps take place in this section to prepare the raw milk for the various products. The results of this section are intermediate milk products with different properties. An important processing step is separation, wherein the milk is cleaned and separated into cream and skim milk. Different kinds of thermal treatments extend the shelf life of the later products. These thermal treatments include, for example sterilisation, pasteurisation or thermisation. In fact, process heat and cooling demands alternate over several consecutive processes with a wide range of temperature levels. Separators are filled with 50°C warm milk while the UHT requires temperature levels up to 140°C (Table C.11).

Table C.11: Process temperature of preparation*

	Min. Temperature	Max. Temperature
Process Heat	~ 50°C	140°C
Cooling	-	4°C

*(cf. Foissy, 2005)

Cooling and Storage

Before processing of the final milk products starts, the intermediate products are stored again and therefore cooled down to a level comparable to that in the first section (Table C.12).

Table C.12: Process temperature of cooling and storage*

	Min. Temperature	Max. Temperature
Process Heat	-	-
Cooling	<4°C	4°C

*(cf. Foissy, 2005)

Product Processing and Finishing

Each milk product requires tailored processing to provide a specific treatment; each has different energy demands and varying temperature levels (Table C.13). The tailored approach extends from 'simple' products like consumer milk to complex fermented milk products (e.g., yogurt, curds, and cheese).

Table C.13: Process temperature for processing and finishing

	Min. Temperature	Max. Temperature
Process Heat	~ 30°C	~ 60°C
Cooling	<4°C	4°C

*(cf. Foissy, 2005)

Cooling and Storage

Most of the dairies maintain large storage capacity to handle time delays between finishing of the milk products and distribution. Depending on distribution and shelf life of the products, storage of a few hours to several days is possible. Hence, the finished products must be cooled down before transferring to the storage buildings and then continuously kept cool while in storage (Table C.14).

Table C.14: Process temperature for cooling and storage*

	Min. Temperature	Max. Temperature
Process Heat	-	-
Cooling	- 10°C	4°C

*(cf. Foissy, 2005)

Similar to the additional process sections described for breweries in Appendix B, also dairies need CIP equipment and require SH as well as DHW. Therefore, the same temperature levels can be assumed.

C.4 Energetic analysis – energy consumer of LGH-network

The dairy runs a LGH-network for several years. This network is an important part of the process heat supply and full integrated to the dairy. Waste heat combined with steam energy supply several consumer groups. The initial situation is therefore something different compared to the brewery and the application of the methodology focus on this network.

Table C.15 summarises again the network parameters. As analysed before, the prior heat sources is the cooling of condensate from steam distribution network. It reaches a maximum heat capacity of 950 kW_{th} and is dependent on the steam demand of the dairy. Covering all heat capacity demand of the consumers, the second source is a steam supply with twice 2,000 kW_{th}. The consumer demand a heating capacity during regular operation between 400–1,600 kW_{th}. It rises in winter because of the space heating up to 2,500 kW_{th}. The flow temperature of the LGH-network is defined at 65°C and the return temperature varies between 45–62°C for regular operation.

The energy consumers are gathered to four consumer groups. Hot water and space heating are complete supplied by the network. CIP gets energy for preheating acid and brine (used as cleaning agent). Production contents preheating processes of intermediate products. In a two-step heat supply, the LGH network supplies as much energy as possible and a respectively temperature given in Table C.15.

Table C.15: Parameter of the LGH-network

Heat capacity *(sources)*	$\dot{Q}_{th,\max}$	Condensate	950 kW_{th}
		Steam *(main)*	2,000 kW_{th}
		Steam *(backup)*	2,000 kW_{th}
Flow temperature	T_{flow}		65°C
Return temperature	T_{return}		45–62°C
Heat capacity *(consumer demand)*	$\dot{Q}_{th,\max}$	peak load	2,500 kW_{th}
	$\dot{Q}_{th}$	regular operation	~ 400–1,600 kW_{th}
	$\dot{Q}_{th,\min}$	minimum load	80 kW_{th}

The steam distribution network finally provides the remaining process heat demand. The heat demand of each consumer group illustrated in Table C.16 represents a maximum and depends on duration as well as simultaneousness of the processes behind. Regarding this, the overall peak load of the network was at 2,500 kW_{th} and reached during regular operation 1,600 kW_{th} (Table C.16).

Table C.16: Configuration of Heat Consumer

	Target Temperature T_{tar}	Heating Capacity $\dot{Q}_{th,\max}$	Duration t_{dur}
Production	> 60°C	525 kW_{th}	
CIP	> 60°C	1750 kW_{th}	0.5–2 h
Hot water	60°C	830 kW_{th}	cont.
Space heating	24°C	1000 kW_{th}	as required

Figure C.13 shows the current configuration of the LGH-network. The serial heat supply with condensate cooling and steam energy considers the priority of condensate cooling. Important is additional the heat storage. This component is not in use and ready for an integration in a SPH-system.

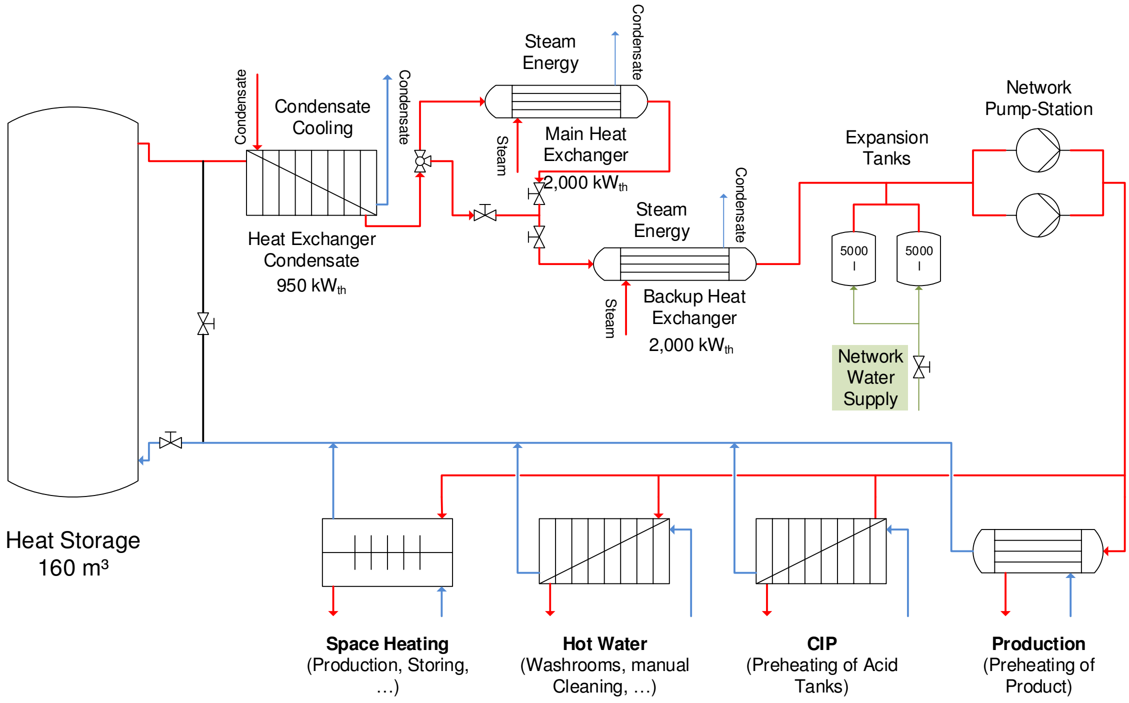


Figure C.13: Schematic of LGH-network configuration

C.5 Energetic optimisation – analysis of waste heat sources

With a steam energy demand of 3,481 MW$_{th}$ in 2011, the optimisation of the LGH-network aims to substitute this steam energy with other sources. This can be defined as initial optimisation potential. This aims on a reconfiguration of the LGH-network and considers the priority of condensate cooling. This are in a first step waste heat sources.

Heat recovery from chiller

Two chiller systems for space cooling and ice water preparation supply cooling energy. Each system consists of several compression chiller and is therefore flexible with cooling capacity. The design data of the systems (Table C.17) are defined concerning prevailing ambient conditions and cooling demand for an optimum system operation. Design and purpose of the systems are comparable to the brewery. However, with higher hot gas temperature and large cooling capacity, also large heat recovery potentials are available.

Table C.17: Design data of chiller systems

		Space cooling	Ice water
Cooling Capacity	$\dot{Q}_0$	3,540 kW_{th}	3,489 kW_{th}
Propulsion Power	P_{el}	960 kW_{el}	1,225 kW_{el}
Evaporation Temperature	T_{evap}	- 17°C	- 13°C
Condensation Temperature	T_{cond}	21.5°C	21.5°C
Refrigerant Mass Flow	$\dot{m}_{ref}$	3.1 kg s^{-1}	3.04 kg s^{-1}
Hot Gas Temperature	T_{gas}	80°C	75°C

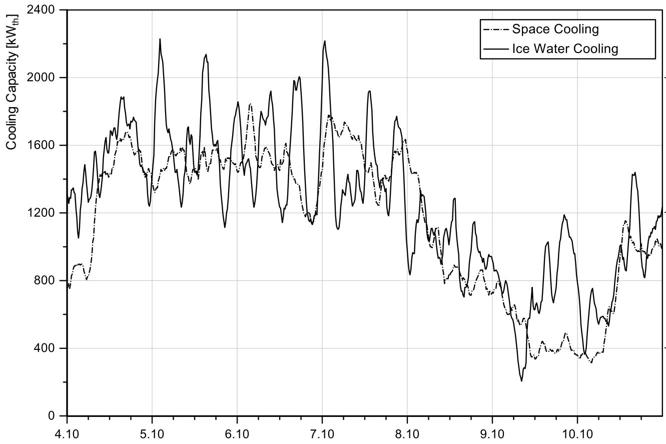
The deheating temperature is defined at 50°C with regard to the return temperature of the LGH-network. Combined with hot gas temperature and refrigerant mass flow, a heat recovery of 237 kW_{th} for space cooling system and 194 kW_{th} for ice water system is available theoretically (Table C.18).

Table C.18: Heat Recovery Potential from Hot Gas Deheating

		space cooling	ice water
Deheating Temperature	T	50°C	50°C
Deheating Enthalpy	Δh	77 kJ kg^{-1}	64 kJ kg^{-1}
Maximum Heat Recovery	$\dot{Q}_{hr,th}$	237 kW	194 kW

The analysis of the chiller systems results a maximum cooling capacity of 2,100 kW_{th} (space cooling) and 2,700 kWh_{th} (ice water). Typically, the cooling capacity varies with production volume between 400–2000 kWh_{th} for both systems (Figure C.14). Hence, the available heat recovery of the total system can just reach 245 kW_{th} (57% of maximum heat recovery) and falls to 49 kW_{th} (11.5% of maximum heat recovery).

The heat recovery factor hrf is 0.2 and defined for the total system (equation (B.1)). With a propulsion energy demand of 5,707 MWh_{th} in 2011 and considering a transmission efficiency of 0.9, heat recovery energy is 1,027 MWh_{th} (equation (B.2)). Heat recovery is not constant and a result of fluctuating weekly load profile (Figure C.14). Further influence has annual load profile (Figure C.15), what follows a higher production volume and a larger cooling demand in summer.



	Heat Recovery Potential		
	Space Cooling	Ice Water Cooling	Total System
$\dot{Q}_{hr,th}$	135 kW	110 kW	245 kW
	~ 57 %		
$\dot{Q}_{hr,th}$	80 kW	66 kW	146 kW
	~ 34 %		
$\dot{Q}_{hr,th}$	27 kW	22 kW	49 kW
	~ 11.5 %		

Figure C.14: Cooling capacity of chiller systems (exemplary production week)

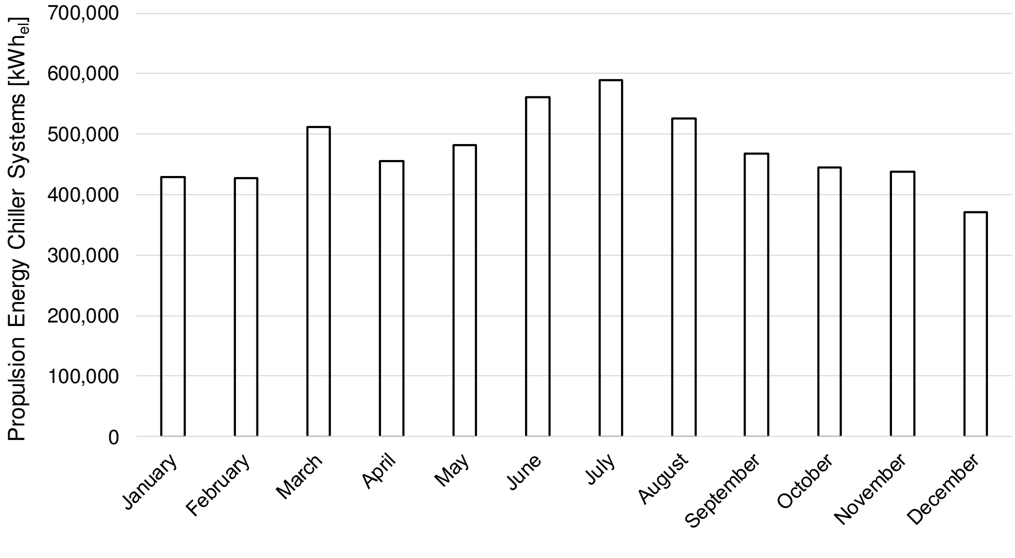


Figure C.15: Propulsion energy of dairy chiller system (2011)

Heat recovery from compressed air system

Two system of each three and four compressors supply compressed air. The compressors run according to compressed air demand alternating or parallel. Air capacity and propulsion power define the system parameter (Table C.19). A liquid cooling circuit connected to the compressors is basis for the heat recovery. The compressors need a cooling temperature of 30°C. Heat recovery is possible with all air compressors. The heat recovery potential depends on the flow temperature and the mass flow of the cooling liquid as well as the effective heat recovery temperature. Regarding the LGH-network, this is comparable to heat recovery from cooling system 50°C. Hence, a full heat recovery is with the necessary cooling temperature not feasible.

Table C.19: Design data compressed air system

		System I	System II
Air Capacity	$\dot{V}_{air}$	4,510 m² h⁻¹	5,550 m² h⁻¹
Propulsion Power	P_{el}	591 kW_{el}	634 kW_{el}
Cooling Temperature	T	30°C	30°C
Compressor Cooling	-	liquid	liquid

Figure C.17 and Figure C.17 shows a temporary data acquisition of the one compressor cooling circuit. The flow temperature varies between 52°C and 80°C. This enables in combination with the mass flow of the cooling liquid a heat recovery of 210 kW_{th} at full system operation.

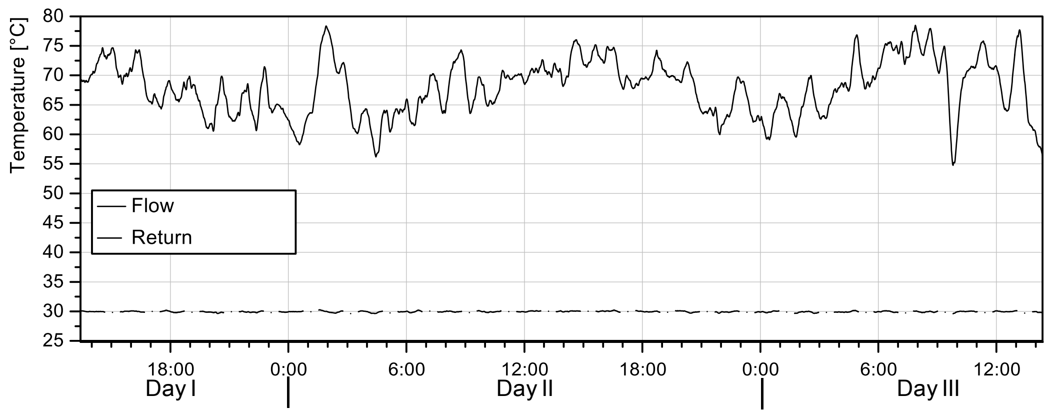


Figure C.16: Exemplary analysis of compressor cooling circuit flow and return temperature

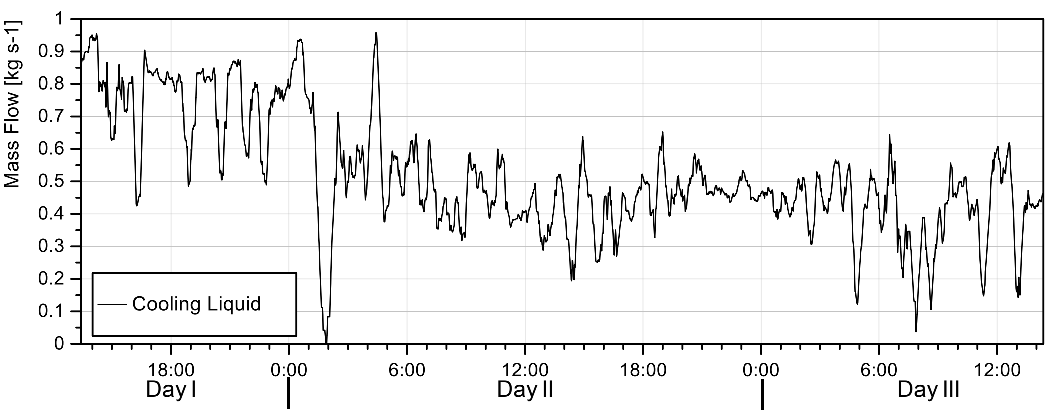


Figure C.17: Exemplary analysis of compressor cooling circuit mass flow cooling liquid

The heat recovery factor hrf is developed with the exemplary analysis above. Depending on available data from the dairy, the factor is based on propulsion energy for the compressors (equation (C.1)).

$$hrf_{Qel,ca} = \frac{Q_{hr}}{Q_{el}} \qquad \text{(C.1)}$$

Heat recovery energy Q_{hr} is determined with 1,810 kWh_{th} for the analysed period (Figure C.17). The propulsion energy demand is 10,460 kWh_{el} for the same period. This leads to a heat recovery factor $hrf_{V,ca}$ of 0.173.

With a propulsion energy demand of 5,567 MWh_{el} (2011) and a transmission efficiency of 0.9, the potential for heat recovery energy is 867 MWh_{th} (equation (C.2)).

$$hr_{ca,energy} = hrf_{Qel,ca} * Q_{el} * \eta_{trans} \qquad \text{(C.2)}$$

The behaviour of the weekly load profile (Figure C.18) is comparable to the load profile of the chiller systems (Figure C.14). Compared to the maximum propulsion power (Table C.19) the figure gives heat recovery capacity at different levels of propulsion power. The annual load profile shows a more constant course (Figure C.19) than that for cooling systems, as compressed air is independent from ambient temperature.

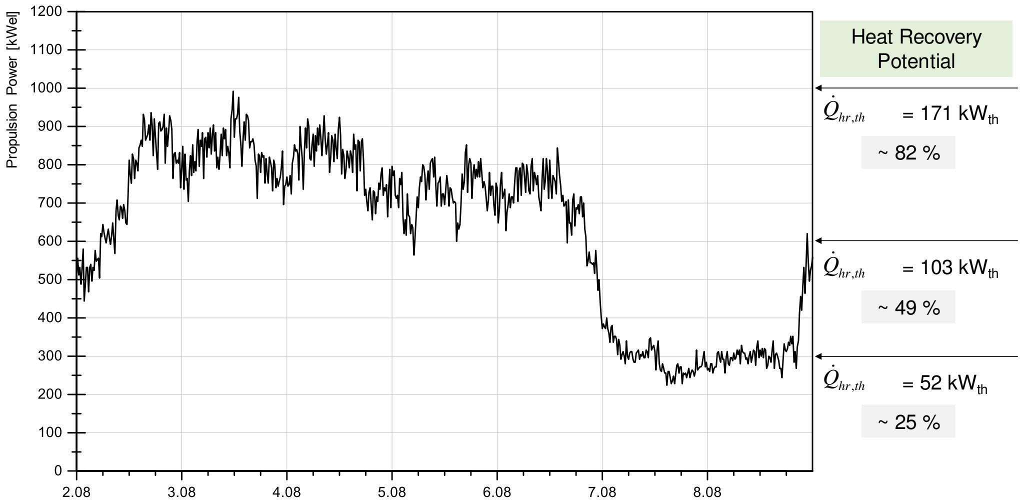


Figure C.18: Propulsion power of air compressor system (exemplary production week)

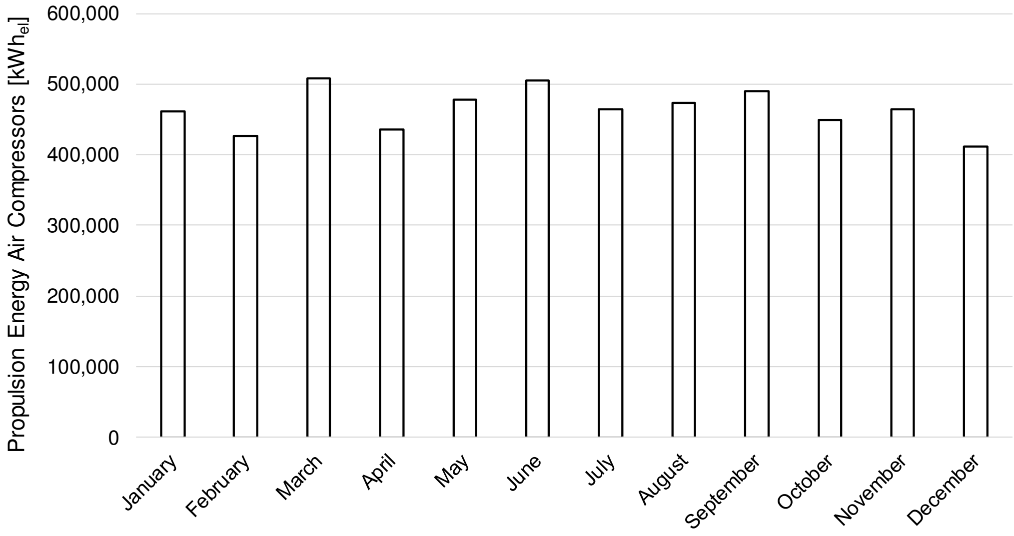


Figure C.19: Propulsion energy air compressor system (2011)

C.6 Energetic optimisation – energy balance

Both heat recovery from cooling systems and air compressor systems provide large potentials of waste heat. Table C.20 shows a balance of potentials of heat recovery compared to the current heat supply of the LGH network. The waste heat potential would be enough to cover almost 55% of the steam energy demand. This means with favourable conditions a remaining steam energy demand of 1,587 MWh_{th}.

Table C.20: Heat recovery potential of LGH-network (2011)

		Heat recovery	LGH-network
Chiller	$hr_{ch,energy}$	1,027 MWh_{th}	
Air Compressor	$hr_{ca,energy}$	867 MWh_{th}	
Condensate Energy	Q_{th}		3,387 MWh_{th}
Steam Energy	Q_{th}		3,481 MWh_{th}

C.7 Energetic optimisation – heat source evaluation

The following example explains the energetic evaluation of two heat sources. The LGH-network of the dairy represents the consumer. With a continuous network operation, the heat capacity is between 250–1,600 kW_{th}.

$Source_1$ (Table C.21) is the condensate cooling of the LGH-network. The flow temperature of the condensate is almost constant at 103°C and fulfils the temperature demand of the LGH-network. However, a maximum heat capacity of 810 kW_{th} at a return temperature of 40°C is not enough for the heat capacity demand. The network as consumer is not able to fulfil the cooling temperature and cooling capacity demand of the condensate. Availability of condensate cooling and duration of LGH-network are both without interruption and enable any time an energy exchange. However, both heat demand of consumer and cooling demand of source cannot be covered complete and need backup units.

Table C.21: Exemplary evaluation: Heat $source_1$ condensate cooling

		$Source_1$	Consumer	Evaluation
Temperature (heating of consumer)	T	103°C	65°C	*sufficient*
Temperature (cooling of source)	T	40°C	45-62°C	*limited*
Heating Capacity	$\dot{Q}_{th}$	810 kW_{th}	1,600 kW_{th}	*limited*
Availability / Duration	t	non-stop	non-stop	*simultaneous*

$Source_2$ (Table C.22) is the heat recovery from air compressors with a source temperature between 62–73°C and not continuous enough for the consumer. The maximum heat capacity of $source_2$ is 350 kW_{th} with a return temperature of 30°C. The availability of heat recovery from air compressors is without interruption and enable any time an exchange of energy. However, heating capacity demand of consumer and cooling demand of source cannot be covered complete and require both backup units.

Table C.22: Exemplary evaluation: Heat source$_2$ heat recovery air compressors

		Source$_1$	Consumer	Evaluation
Temperature (heating of consumer)	T	62-73°C	65°C	*limited*
Temperature (cooling of source)	T	30°C	45-62°C	*limited*
Heating Capacity	Q_{th}	350 kW_{th}	1,600 kW_{th}	*limited*
Availability / Duration	t	non-stop	non-stop	*simultaneous*

The condensate cooling is of a higher quality in this example. It is to prefer in comparison with the heat recovery from air compressors. Hence, heat recovery from air compressors is added on the condensate cooling.

C.8 Energetic optimisation – concepts of low-grade heat network

Using the defined potentials of waste heat assumes a favourable integration to the network. In contrast to the low-grade heat supply of the brewery (Appendix B), the dairy networks conditions are with a much higher return temperature more disadvantageous. The concept development of optimised LGH-network considers therefore several objectives:

- network flow temperature remains at 65°C
- maintain current LGH-network configuration as far as possible
- same process heat consumers as in basis configuration
- maximum use of waste heat, without reducing condensate cooling
- direct integration of waste heat sources
- steam energy supplies remaining energy demands

A similar behaviour of load profiles of LGH-network and waste heat sources enable that direct waste heat integration. A heat storage is therefore not necessary. With a serial as well as a parallel waste heat integration, two system approaches are developed and further analysed within the simulation.

Figure C.20 illustrates a direct implementation of heat recovery between condensate cooling and steam energy. This serial connection is the first approach and means a sequential heat supply.

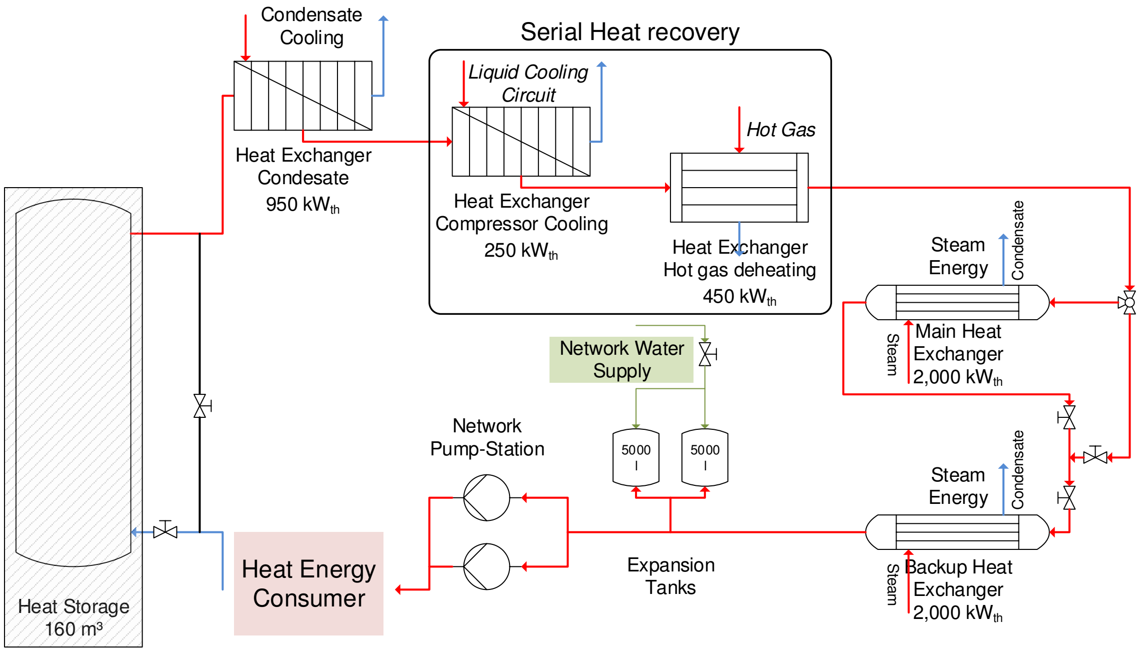


Figure C.20: Concept LGH-network with serial heat recovery

The integration of waste heat in the second concept approach is parallel (Figure C.21). This requires a division of the LGH-networks mass flow before but shall provide better conditions to both waste heat sources.

The determination of heat recovery potentials in Table C.20 do not consider the time dependence of heat recovery and energy supply to the LGH-network. Methods of the pinch analysis as used for the brewery concept are not helpful with strong fluctuating energy demand of the LGH-network as well as heat recovery source. However, an evaluation of the interdependent heat sources is essential and therefore part of the simulation based system.

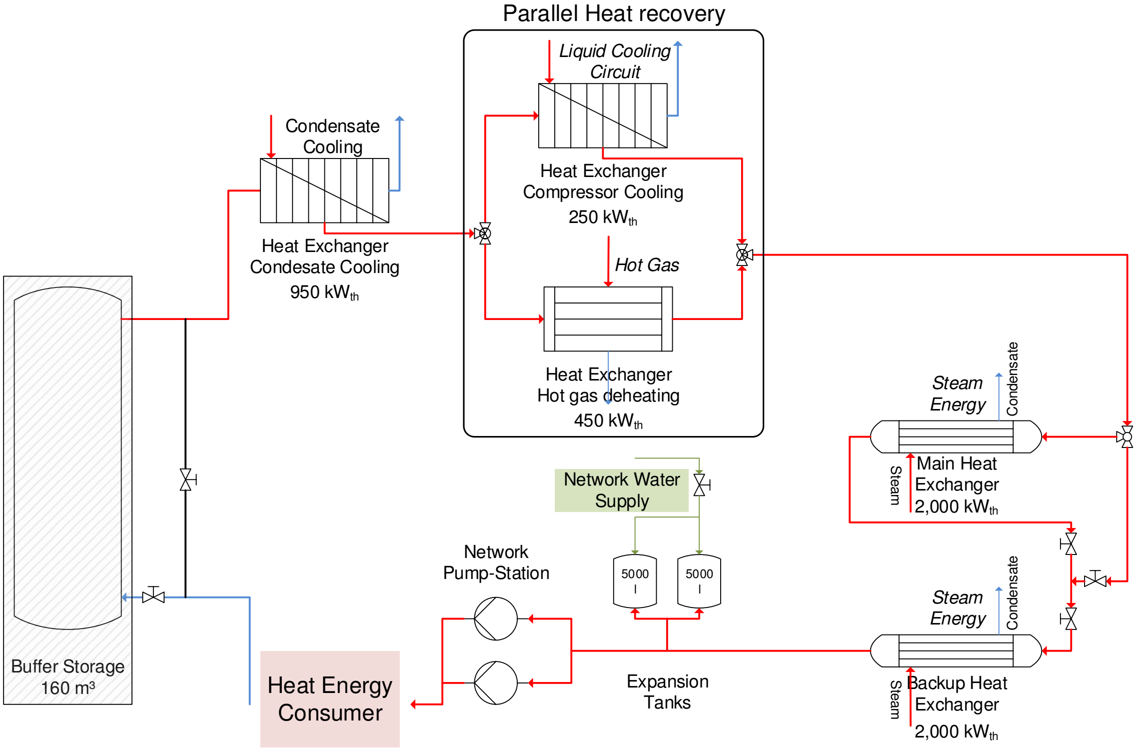


Figure C.21: Concept LGH-network with parallel heat recovery

C.9 Energetic optimisation – concept evaluation

A LGH-network as at the dairy provides a promising background. The network supplies process heat to almost all relevant consumers, a heat storage is available for any use and the flow temperature is a moderate level of 65°C. A disadvantage for all heat source integration is the return temperature as analysed that clearly limits the waste heat potential of chiller systems and air compressors. The behaviour of LGH-network load profile enable a direct connection of waste heat source with similar load profile. Storing the waste heat is not advisable. Two concept approaches show the possibilities of serial and parallel heat recovery. A serial integration is technical more easy to realise, but has disadvantages for the second source because of a higher return temperature. A parallel integration is first a challenge for the flow control. It requires an optimised diversion of the network mass flow to supply both waste heat sources with favourable return flow temperatures. Both variations are technically feasible with small reconfigurations.

This will also be supported by a central heat station as initial point for the LGH-network at the production site.

The energetic benefit is not as obvious as with the breweries LGH-supply concept. This is a result of the return flow temperatures of the network and does not enable a simple estimation of heat recovery. As Table C.20 illustrates, heat recovery energy would be enough to substitute almost 55% of the steam energy. This however, would require much lower return temperatures than available with the current configuration. Hence, the energetic potential is smaller and can only be determined with the simulation.

Necessary technical equipment and components are standard for heat recovery from air compressors and cooling systems. The investment can be defined as low. A difference is between the serial and parallel integration. The hardware is comparable for both but the control system is more complex for the parallel one and entails higher costs for installation, commissioning and operation.

C.10 Solar process heat system - analysis of roof area

The method of analysis is the same as at the brewery. The *Usage Factor II* is with 0.13 much lower than at the brewery, what is a result of many substructures on the roof. As the base area is 37.400 m², the maximum collector area is with 4,860 m² comparable to the brewery. The energy storage is outside the building and located direct to the boiler room (Figure C.22). Most of the piping can be installed inside the building. The structural conditions are also promising for solar process heat integration.

The analysis results a show large area available for collector mounting and with a central boiler rooms including unused heat storages promising conditions for the implementation of SPH-systems.

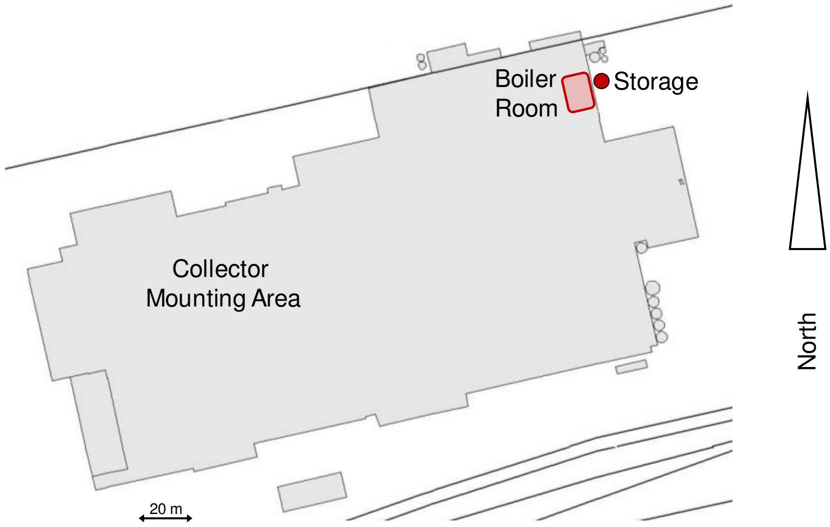


Figure C.22: Layout with collector mounting areas (cf. Bayernatlas, 2013)

C.11 Solar process heat system - SPH-system configuration

Initial point for the SPH-system configuration is also an existing tank (Table C.23). The heat energy storage of the LGH-network is not in use with the current configuration but flown through by the heat transfer medium. The reconfiguration of the network decouples the storage and it is available for the SPH-system. The storage is located outside the company buildings. Site specific weather data enable to consider the influence of ambient temperature conditions and to evaluate energy losses of the storage.

Table C.23: Configuration heat energy storage

Heat Energy Storage	Volume	$\dot{V}$	160	m^3
	Diameter		4	m
	Heat Loss Coefficient	u	1.2	$W\,m^{-2}\,K^{-1}$
	Connection	pipe connection		
Weather Data	Location Mertingen (longitude -10.78, latitude 48.65)			
	Annual data record (Remund, 2012)			

The storage volume is background for the design of the collector area. The orientation of the collector array is adapted to the building conditions. The input parameters for collector and storage circuit are from the general system configuration background in Appendix A. Table C.24 gives the final configuration parameter. That is further input for system modelling and simulation.

Table C.24: Configuration parameters SPH-system

Collector Area	Collector Type	-	Flat-Plate	
	Collector Array	A	2.005	m^2
	Orientation	-	-10	°
	Inclination	-	45	°
Collector Circuit	Heat Transfer Medium	-	Water-Glycol-Mixture	
	Volume Flow Rate	$\dot{V}$	25	$l\ h^{-1}\ m^{-2}_{ca}$
Heat Exchanger	Flow Type	-	Counter	
	Constant Heat Transfer	$u_{a,0}$	175	$kW\ K^{-1}$
	Mass Flow hot	$\dot{m}$	13.9	$kg\ s^{-1}$
	Mass Flow cold	$\dot{m}$	12.8	$kg\ s^{-1}$
Storage Charging Circuit	Heat Transfer Medium	-	Water	
	Volume Flow Rate	$\dot{V}$	23	$l\ h^{-1}\ m^{-2}_{ca}$
Piping	Outside	L	460	m
	Inside	L	400	m
	Heat loss Coefficient insulation	UA	0.35	$W\ m^{-2}\ K^{-1}$

C.12 Solar process heat system - reconfiguration of low-grade heat supply

The integration of the SPH-system is based on the reconfigured LGH-network from energetic optimisation. The approach defines an integration point for solar process heat to the LGH-network after heat recovery. This is for the serial but also for the parallel heat recovery and considers with this the priority of heat recovery. The interdependence of heat recovery and solar thermal heat supply is a major aspect of the further system analysis with the simulation. Figure C.23 illustrates a simplified subsystem structure that illustrates the flow direction of LGH-network with parallel heat recovery from air compressors and cooling system as well as the final backup after solar process heat.

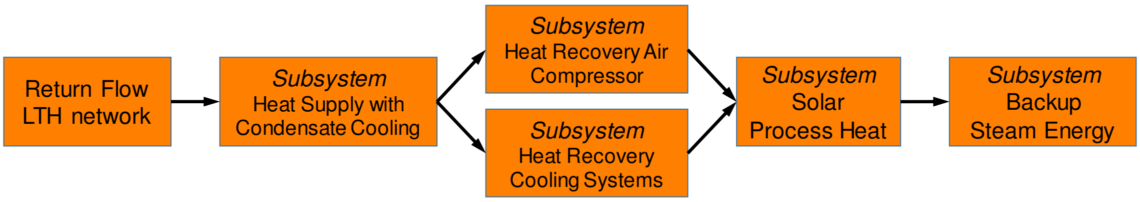


Figure C.23: Subsystem structure LGH-Network with heat recovery and solar process heat

C.13 System simulation – simulation of basis system

The annual simulation of the basis system results a good correlation of energetic data from the real network and the simulation model. The divergence regarding data acquisition (basis: energy balance) and annual simulation is at 2.1% for condensate energy and 5.7% for steam energy supply (Table C.25). For the complete LGH network, this means a divergence of 3.9%.

Table C.25: Comparison of simulation and LGH-network data

Energy Supply	2011 Data acquisition	Simulation prepared load profile	Divergence real data to simulation
Heat Recovery form Condensate Energy	3,387 MWh_{th}	3,458 MWh_{th}	2.1%
Steam Energy	3,480 MWh_{th}	3,678 MWh_{th}	5.7%

An unknown quantity is the energy loss of the storage. This is not part of the dairy data acquisition and only considered during the simulation. This energy loss must considered as unknown proportional divergence.

That correlation of simulation data and real data is also for the heat capacities of the LGH-network. As Figure C.24 illustrate, the heat capacities deviate just slightly from each other and show a similar course. The major reasons for the deviation of simulation data from real data are figured out with

- the temperature variations of the LGH network in comparison to the smoothed temperatures for simulation,
- a more exact target temperature within the simulation,

- and the difference of step size between simulation and data acquisition.

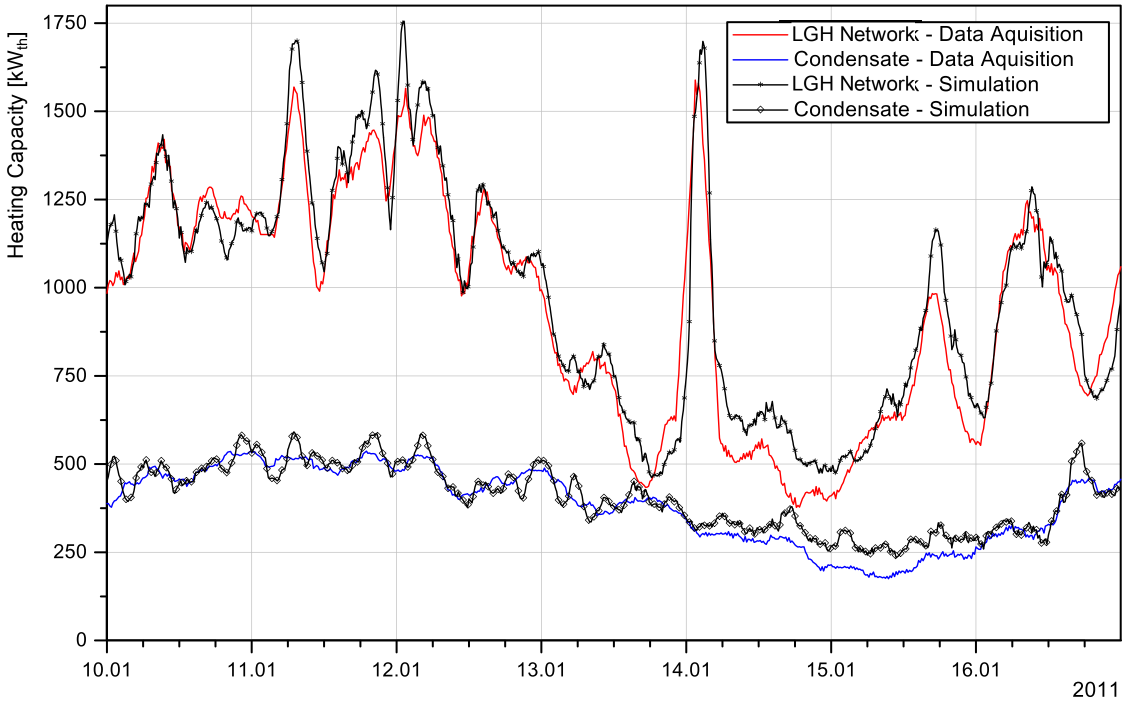


Figure C.24: Heating capacities of LGH-network – comparison of simulation and real network data

Temperature variations, heat capacity and energy balance validate a sufficient overall behaviour of the system model. Hence, it is usable for a reconfiguration to a sustainable network.

C.14 System simulation – simulation of reconfigured variations of LGH-supply

Waste heat and solar process heat are the sources to implement for a sustainable LGH-network. Several variations of heat source configurations possible but also dependences arise between them regarding their efficiency. The simulation enables analysing each heat source individually as well as their interaction within the background of the LGH-network.

The priority of condensate cooling requires an integration of all waste heat sources after that. An individual analysis of waste heat from air compressors and cooling systems is the first approach and shows the essential configuration possibilities. As Figure C.25 illustrates, this means different variations of heat source connection. Reference is an individual integration of each heat recovery source to determine the total capacity (ID ac and cs). Based on this, the heat recovery sources are combined in several variations of serial connection (ID ac-cs and cs-ac) as well as parallel connection (ID ac+cs).

	Variations of Heat Source Connection				
Model ID	ac	cs	ac-cs	cs-ac	ac+cs
Condensate Energy	1	1	1	1	1
hr Air Compressor (ac)	2		2 serial	3 serial	2 parallel
hr Cooling System (cs)		2	3	2	2
Steam Energy	3	3	4	4	3

Figure C.25: Heat recovery *hr* source configurations of LGH-network

An analysis of the simulation results of the configuration variations is the first step. Table C.26 compares therefore the individual annual process heat supply of each source to the LGH-networks.

Table C.26: Simulation results of heat recovery variations

Energy Source		**ID ac**	**ID cs**	**ID ac-cs**	**ID cs-ac**	**ID ac+cs**
Condensate Energy	MWh_{th}	3,458	3,458	3,458	3,458	3,458
hr Air Compressor	MWh_{th}	285	---	285	222	278
hr Cooling System	MWh_{th}	---	764	736	758	753
hr	MWh_{th}	285	764	1,021	980	1031
Steam Energy	MWh_{th}	3,291	2,762	2,521	2,570	2,513

The results cannot confirm the potential of heat recovery from air compressors (ID ac) and cooling system (ID cs) as defined with the analysis of waste heat sources. Main reason is the comparatively high network temperature what cuts a lot of the potential. Air compressors achieve within simulation just 32.9% and cooling system at least 74.4% of the potential. A serial connection (ID ac-cs and ID cc-ac) has negative effects on the heat recovery sources. The total energy yield of both serial variations is by 3–6 lower than the individual heat recovery. A parallel arrangement of heat recovery is able to compensate this fact nearly complete. The mass flow of the LGH-network is therefore steady split after condensate cooling. A fraction of 60% mass flow to the *hr* cooling chiller and 40% to the *hr* Air compressor supplies almost 99% of the individual *hr* energy to the network.

In a second step, the analysis of simulation show also good results of temperature increase during heat recovery. Figure C.26 illustrates this for the parallel heat recovery (ID ac+cs) with flow and return temperature for an exemplary period in winter (a) and in summer (b). The temperature increase with heat recovery is 1–4°C. HR is just able to supply the target temperature of the LGH-network selective (blue marking in Figure C.26 (b)). Hence, steam energy is still necessary continuously.

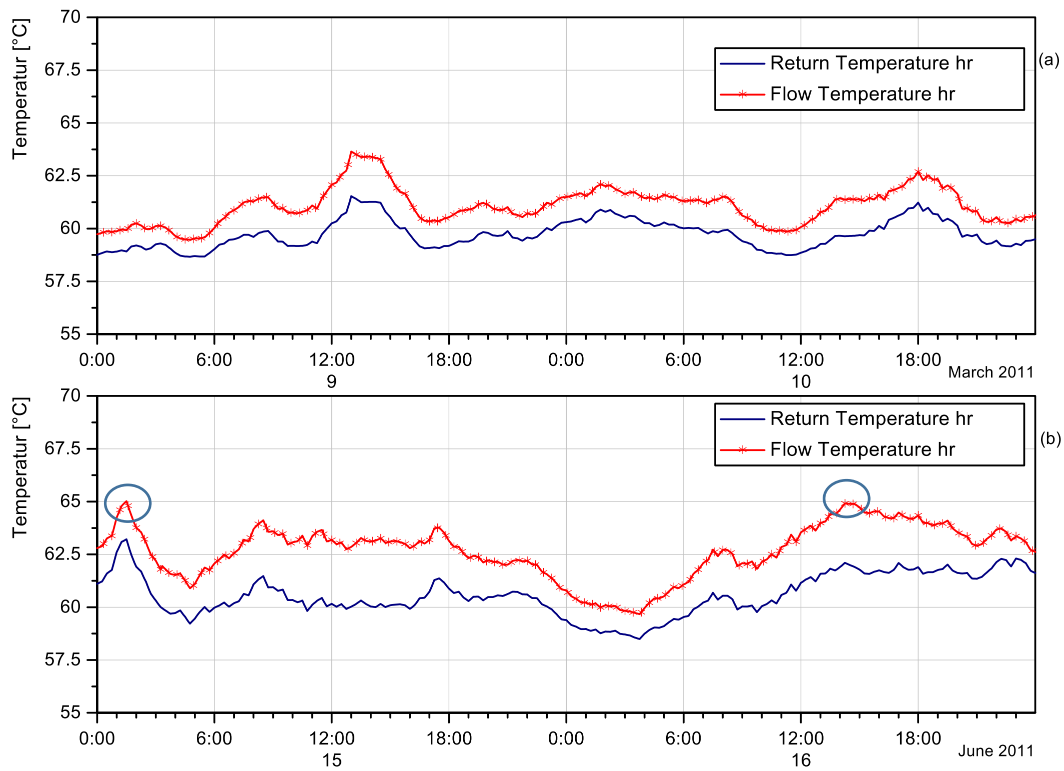


Figure C.26: Return and flow temperatures *hr* for Model ID ac+cs

Figure C.27 shows the corresponding heat capacities of the heat recovery sources with parallel configuration for the two periods (a) and (b). Both hr sources do not meet the heat capacity expectations of the analysis of waste heat sources. *Hr* Air compressor reaches about 50% of the determined heat recovery potential and hr cooling system reaches about 60% of its defined heat recovery potentials.

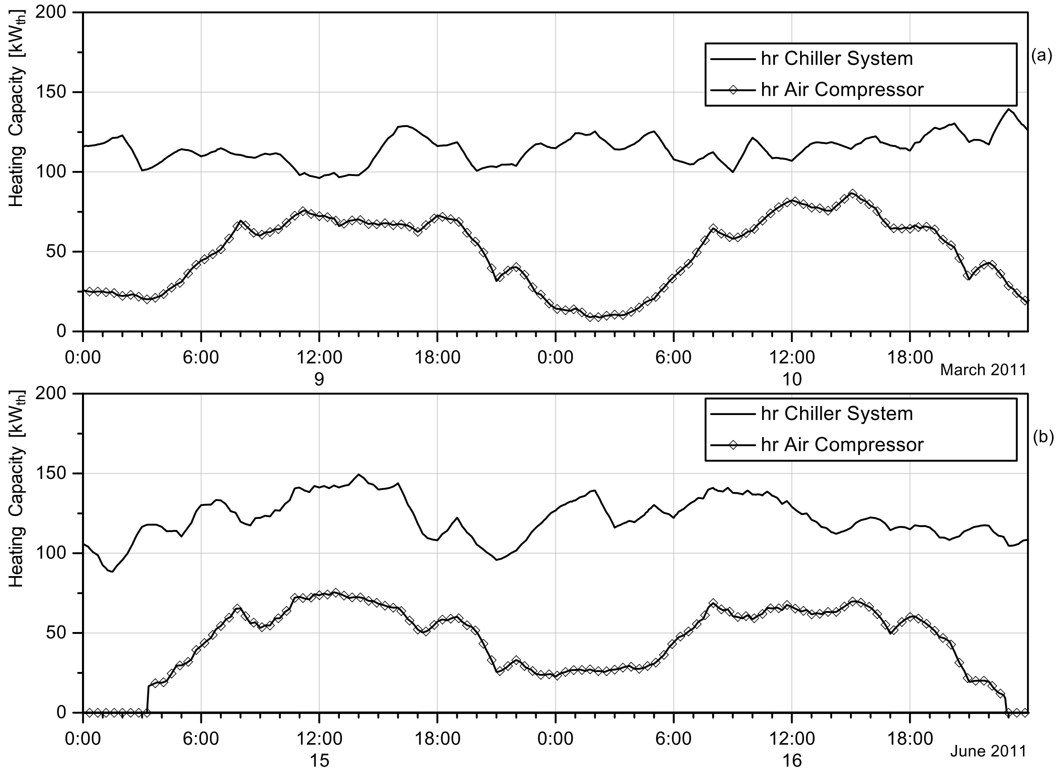


Figure C.27: Heating Capacity of *hr* for Model ID ac+cs

Despite the failed expectations of heat recovery, the parallel combination of heat recovery (ID ac+cs) is a promising basis and defined as configuration for ongoing optimisation.

The priority of condensate cooling applies also for solar energy. Hence, an implementation of the SPH-system is between condensate cooling and the steam energy supply and for an individual analysis (ID st). A serial combination of the parallel heat recovery and solar energy is the second configuration (ID ac+cc-st).

	Variations of Heat Source Connection	
Model ID	st	ac+cc-st
Condensate Energy	1	1
hr Air Compressor (ac) / ***hr*** Cooling System (cs)		2
Solar-Thermal Energy (st)	2	3
Steam Energy	3	4

Figure C.28: Heat source configurations of LGH-network with heat recovery *hr* and solar-thermal energy *st*

Table C.27 compares the results of the annual simulation. System ID st supplies 677 MWh_{th} solar process heat from the collector array to the storage and 520.5 MWh_{th} heat energy from the storage to the LGH-network. This are specific collector earnings of 338 kWh_{th} m^{-2} a^{-1} based on the collector array and 260 kWh_{th} m^{-2} a^{-1} based on the LGH-network energy supply. Energy losses of piping and the storage are 156.5 MWh_{th}.

The configuration of parallel heat recovery and SPH-system after that (ID ac+cc-st) shows clear a decreased solar process heat. As Table C.27 illustrates the energy yield from the collector array is with 611.3 MWh_{th} about 10% lower. The energy supply to LGH-network is at 450 MWh_{th} and even 13.5% lower than without heat recovery (ID st). Respectively are the specific collector earning at 305 kWh_{th} m^{-2} a^{-1} (collector array) and 224 kWh_{th} m^{-2} a^{-1} (LGH-network). Finally, the remaining steam energy reduces from 3.648 MWh_{th} (conventional configuration) by almost 45% to 2,046.2 MWh_{th} (ID ac+cc-st).

Table C.27: Simulation results of variations with solar-thermal energy

Energy Source		**ID st**	**ID ac+cc-st**
Condensate Energy	MWh_{th}	3,458.5	3,458.5
hr Air Compressor	MWh_{th}	---	278.0
hr Cooling Chiller	MWh_{th}	---	753.5
Solar Energy from *collector array*	MWh_{th}	677.0	611.3
Solar Energy to *LGH-network*	MWh_{th}	520.5	449.7
Steam Energy	MWh_{th}	3,052.6	2,046.3

Depending on the location, solar process heat supply is not continuous through the year. The simulation results the largest energy yields from April to August (black frame in Figure C.29). About 67% of the annual energy generation is there. Figure C.29 illustrates the context of location dependent irradiation and the trend line of solar process heat. Essential reason is the available temperature from SPH-system in comparison to the LGH-network temperature to supply energy. This usable temperature is most often reached from April to August.

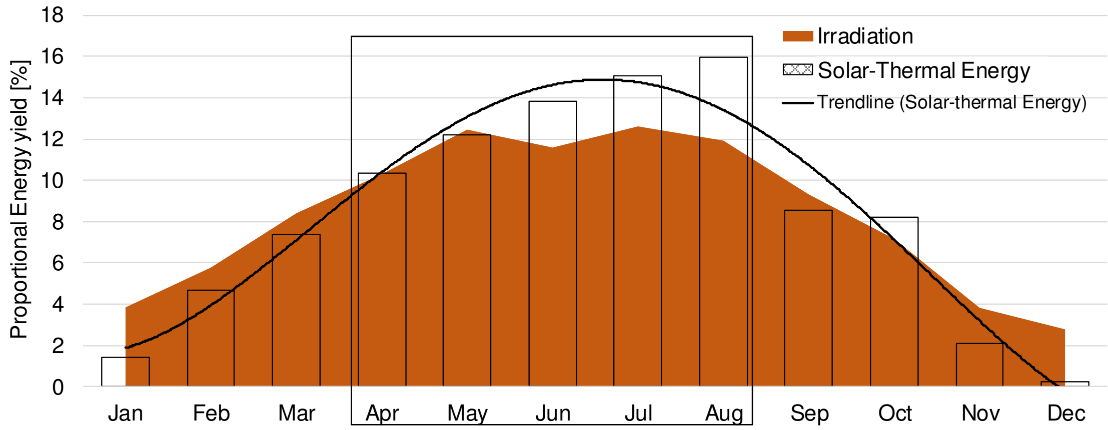


Figure C.29: Proportional solar-thermal energy to LGH-network (Simulation 2011)

This LGH-network temperature at the integration point (ID ac+cs-st) is already on an unfavourable level for solar-thermal performance. Figure C.30 illustrates this for a production week in winter. The return temperature to the solar energy source – what is identical with the LGH-network temperature after heat recovery – is often above the storage temperature. Hence, the available temperature for solar energy supply is to low and the system is just in operation for some short periods.

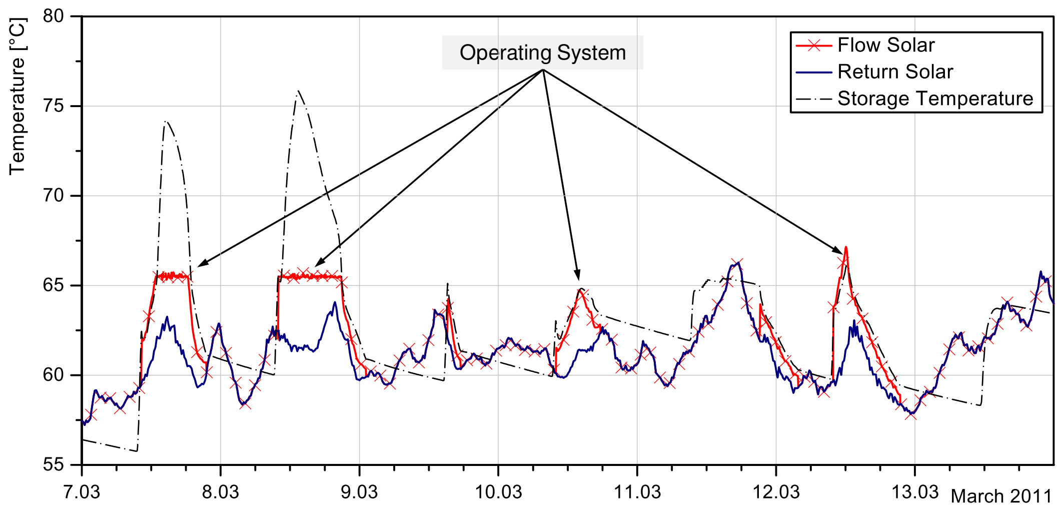


Figure C.30: Temperatures of solar-thermal heat supply in winter (ID ac+cs-st)

The situation changes in summer and operation time raises clearly, when the irradiation is higher. Figure C.31 shows again return and flow temperature of the solar process heat source. The available temperature from the storage is most of the time above the return temperature and sufficient for the defined LGH-network temperature over longer periods. Solar process heat substitutes the steam energy with these conditions.

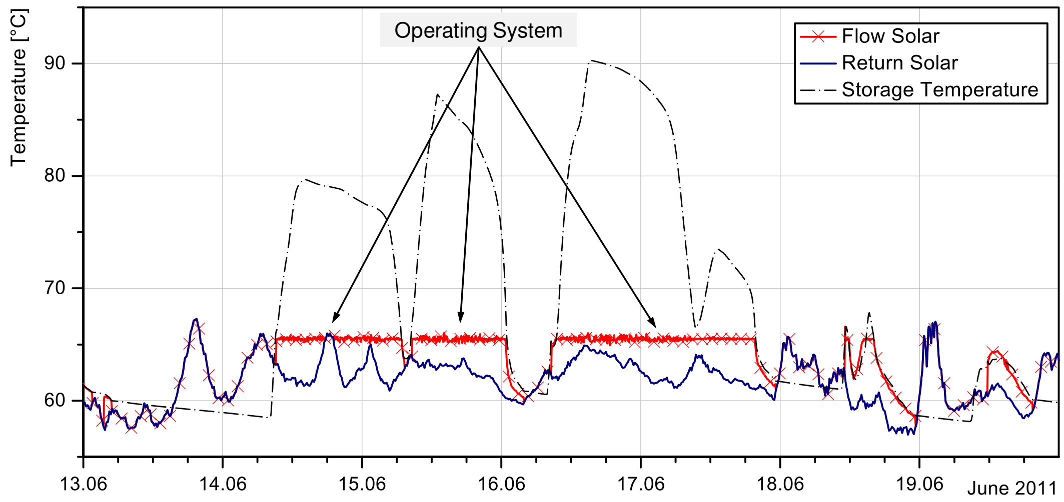


Figure C.31: Temperatures of solar-thermal heat supply in Summer (ID ac+cs-st)

The evaluation of specific heat capacities completes the energetic system evaluation. Equation (B.4) defines the necessary utilisation factor. This is applied for specific heat capacity of the collector array UF_{col} and specific heat capacity of the solar process heat supply to LGH UF_{supp}.

$$UF = \frac{Specific Heat Capacity}{Global Radiation} \tag{C.3}$$

Defined load cases are background for a system analysis. Four typical days (TD) represent this load cases with the global radiation on the inclined collector surface:

- TD 1: global radiation > 1.000 W m^{-2}
- TD 2: global radiation ~ 750 W m^{-2}
- TD 3: global radiation ~ 550 W m^{-2}
- TD 4: global radiation < 400 W m^{-2}

Table C.28 illustrates the specific heat capacities and utilisation factors for each of one typical day. UF_{col} is between 0.39 and 0.53 and UF_{supp} is between 0.21 and 0.23. Hence, the available global radiation can be used for solar process heat supply to LGH-network by 21–25% (TD 4).

Table C.28: TD Evaluation of System Configuration ID ac+cs-st

Maximal		**TD 1**	**TD 2**	**TD 3**	**TD 4**
Global Radiation	W m^{-2}	1,015	725	560	375
Specific Heat Capacity *Collector Array*	W m_{ca}^{-2}	540	335	235	170
	UF_{col}	0.53	0.46	0.42	0.45
Specific Heat Capacity *Solar process heat to LGH-network*	W m_{ca}^{-2}	210	170	135	95
	UF_{supp}	0.21	0.23	0.24	0.25

Figure C.32 – Figure C.35 show the global radition and the heat capacities for exemplary TD 1 – TD 4. The figures illustrate addional the time-shifted use of solar process heat. This is an effect of indirect system configurations with a heat storage.

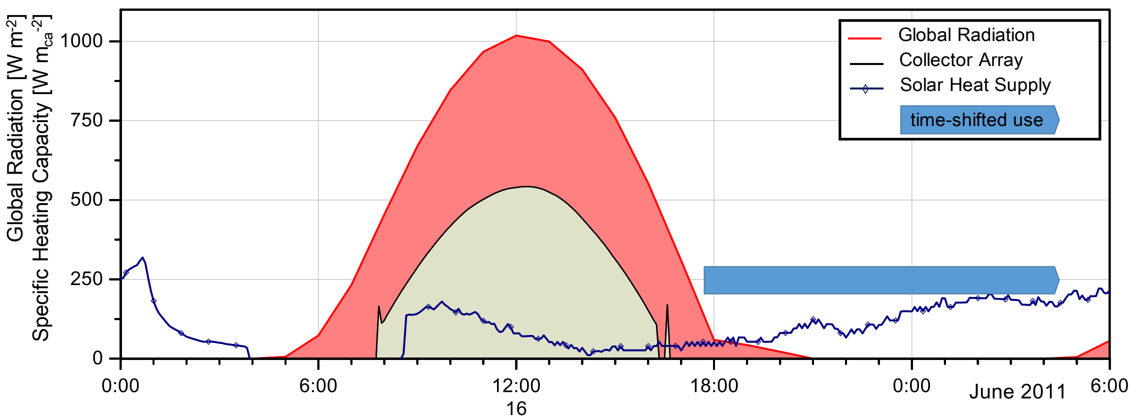


Figure C.32: Global radiation and specific heating capacity TD 1 (ID ac+cs-st)

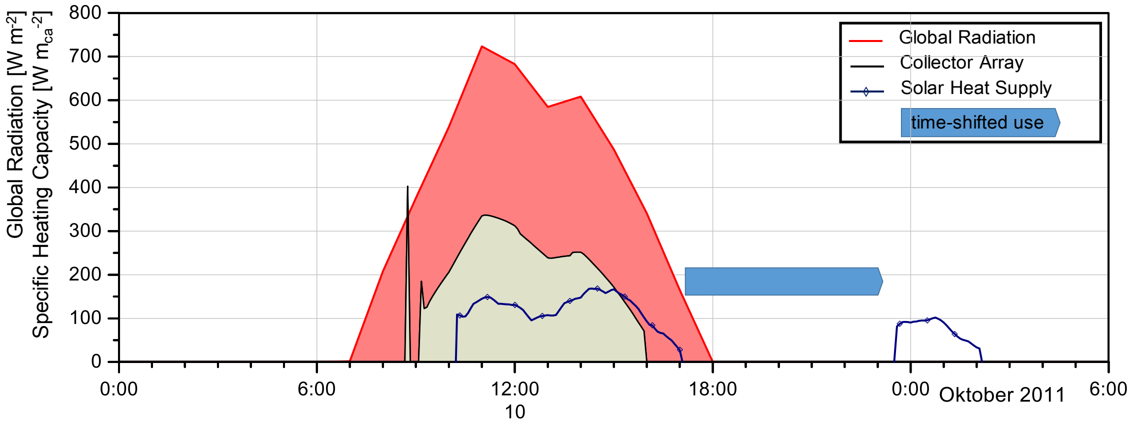


Figure C.33: Global radiation and specific heating capacity TD 2 (ID ac+cs-st)

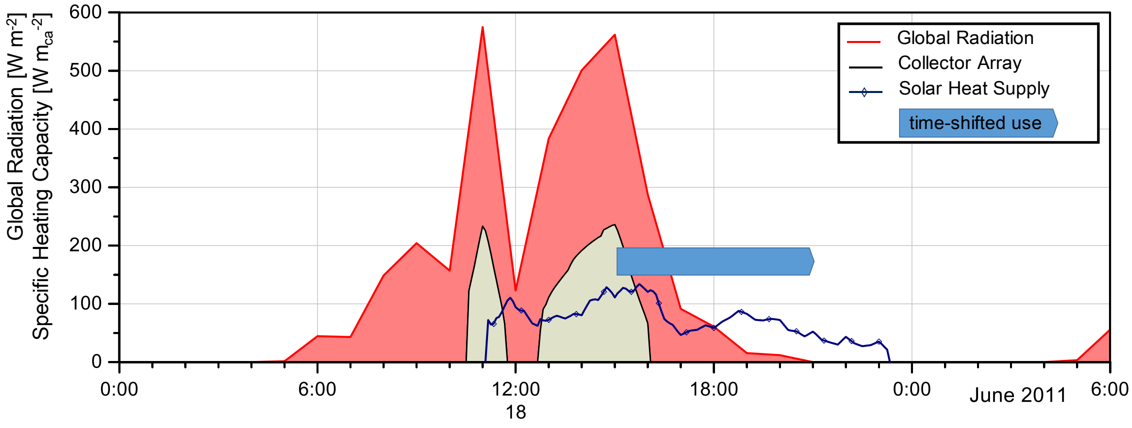


Figure C.34: Global radiation and specific heating capacity TD 3 (ID ac+cs-st)

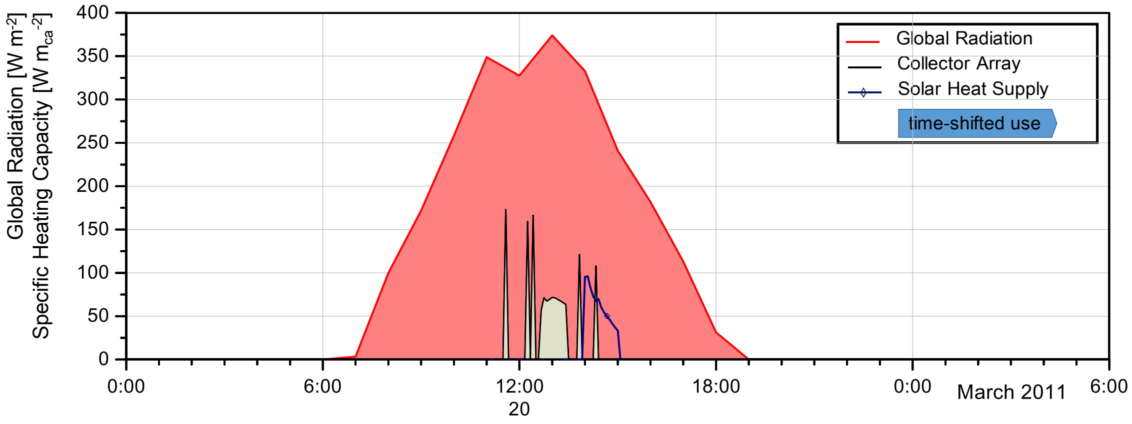


Figure C.35: Global radiation and specific heating capacity TD 4 (ID ac+cs-st)

The SPH-system as designed shows promising results at periods with high global radiation. However, unfavourable conditions of the LGH-network prevent higher solar-thermal energy yields. Additionally, specific heat capacities remain in a similar proportion compared to global radiation as the analysis of the utilisation factor results.

Appendix D Comparative case study results

D.1 Sensitivity analysis

The sensitivity analysis focuses on the SPH-system of the configuration and aims to maximise solar performance without reducing energy use from waste heat sources.

Figure D.1 illustrates the parameter of three systems parts defined for the sensitivity analysis. A high degree of scope provides the collector array. This is for the collector area, collector inclination and orientation. The collector design distinguishes just between flat plate and vacuum tube collectors. A variation of fluid mass flow through the collector is the operation parameter. Parameter for the storage is first its volume and additional insulation as well as charging and discharging system.

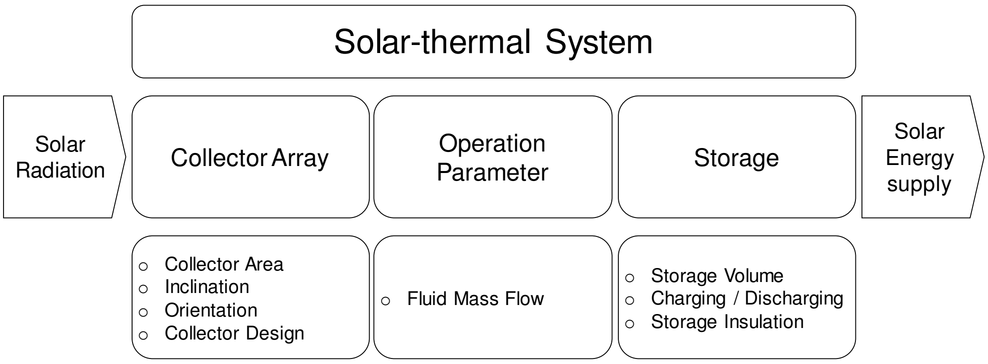


Figure D.1: Parameters for sensitivity analysis of a SPH-system

Considering the parameter variation of the SPH-system, the solar efficiency SOL_{eff} is background for the optimised system performance and is defined as $SOL_{eff,max}$ (equation (D.1)).

$$SOL_{eff,max} = f(Colar, Opar, ST) \tag{D.1}$$

Each parameter is tested and analysed independent. This means for example the variation of the collector area in connection with the other basis parameter of collector array, operation and storage. The specific collector earnings based on the energy to process is the factor for an individual evaluation. This is transferred to the relative specific collector earning (Relative SCE) and defined with 1 to the specific collector earnings (Table D.1). An optimisation potential results with relative SCE increases > 1.

Table D.1: Evaluation basis – relative specific collector earnings

System configuration	**Specific Collector Earnings (SCE)** [kWh_{th} m^{-2}_{ca} a^{-1}]	**Relative SCE** [-]	**Optimisation Potential** [-]
Brewery 'solar bw'	431.2	1	> 1
Dairy 'ID ac+cc-st'	224.3	1	> 1

All the identified optimisation potential is finally input to an optimised system configuration.

<u>Variation of collector area</u>

The collector area is varied on basis of the system configuration ID ac+cc-st (dairy) and ID solar bw (brewery). With a step size of 0.1, the area is scaled down to a minimum factor of 0.3 and scaled up to a maximum factor of 2.0 (Figure D.2).

The brewery configuration ID solar bw represents a system with promising solar-thermal load conditions. Specific collector earnings behave almost linear without a maximum for the analysed range. They increase from 431.2 kWh_{th} m^{-2} a^{-1} (basis parameter) to 625.7 kWh_{th} m^{-2} a^{-1} and decreases to 268.4 kWh_{th} m^{-2} a^{-1}. That high solar collector earing at small an area is – despite a large storage volume – possible with the load conditions of cold brew water as return flow to the SPH-system. This enables solar process heat supply throughout the year. However, growing collector area are effected by a proportional decreasing energy demand, what results in also decreasing specific collector earnings. The favourable proportion of specific collector earnings and total solar process heat supply do not recommend changing the collector area.

The dairy configuration ID ac+cc-st represents a system with limited solar-thermal load conditions. The specific collector earnings are not linear and reach a maximum of 237.7 kWh_{th} m^{-2} a^{-1} at a factor for the collector area of 0.8. With smaller collector area and because of growing specific storage volume, the storage temperature falls more and more below the supply temperature of the LGH-network. The result are dropping specific collector earnings as Figure D.2 illustrates. The curve shape of specific collector earnings at larger collector areas are comparable to the brewery configuration ID solar bw.

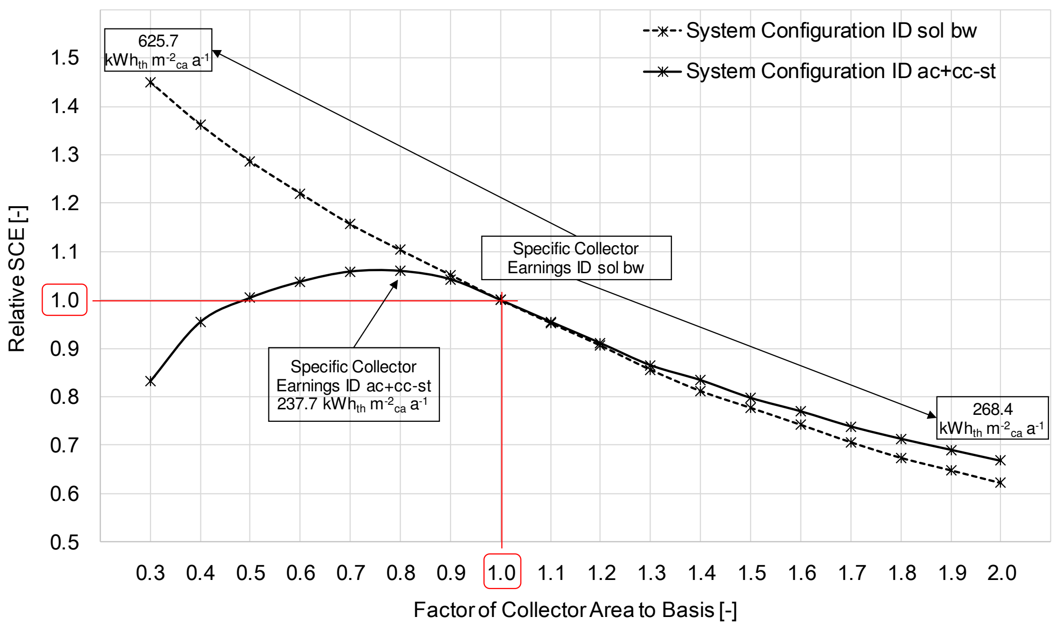


Figure D.2: Variation of collector area

Figure D.3 gives additional the solar fraction for the varied collector area. Basis is the annual solar process heat supply to process and represents its fraction compared to the maximum possibility of solar process heat supply. The solar fraction raises for both system configurations with an increasing collector area but at the same with a decreasing gradient. This illustrates clear the limits of growing collector area. An efficient system ID solar bw with high specific collector earnings at 625.7 kWh_{th} m^{-2} a^{-1} for example mean simultaneous a low solar fraction of 19%. A less efficient system ID solar bw however covers more than 55% of the possible energy demand but with low specific collector earnings at 268.4 kWh_{th} m^{-2} a^{-1}.

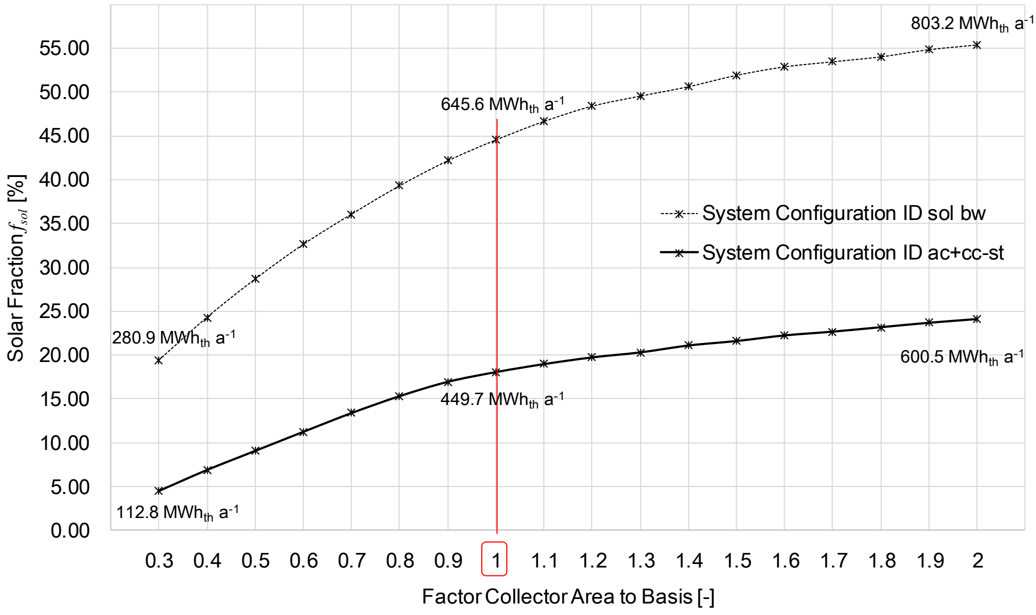


Figure D.3: Solar fraction with variation of collector area

The variation of collector area within the analysed range is technical feasible and not restricted by the available roof area. Large collector areas provide increasing solar process heat supply and increasing solar fraction. However, only smaller collector areas ensure high specific collector earnings and promise an efficient system but with the result of low solar fraction. The results illustrate, that it is not only an exclusively energetic question but also an economic one.

<u>Collector orientation and inclination</u>

Orientation and inclination of the collector effect the solar performance. Both are direct dependent on the location. A system independent analysis provides favourable parameters for an integration in exemplary system configurations.

Figure D.4 shows the parameter result for the brewery location (Ingolstadt, Germany). Best irradiation is with an orientation of 15° southwest and an inclination of 32.5°. Compared to initial parameters (orientation 0° southwest, inclination 45°) this is just an improvement of 2.2%. The implementation of this optimised parameter in an exemplary system confirms that low improvement. Annual energy supply from collector is – with a divergence of 0.3% – nearly the same on basis of the system configuration ID solar bw.

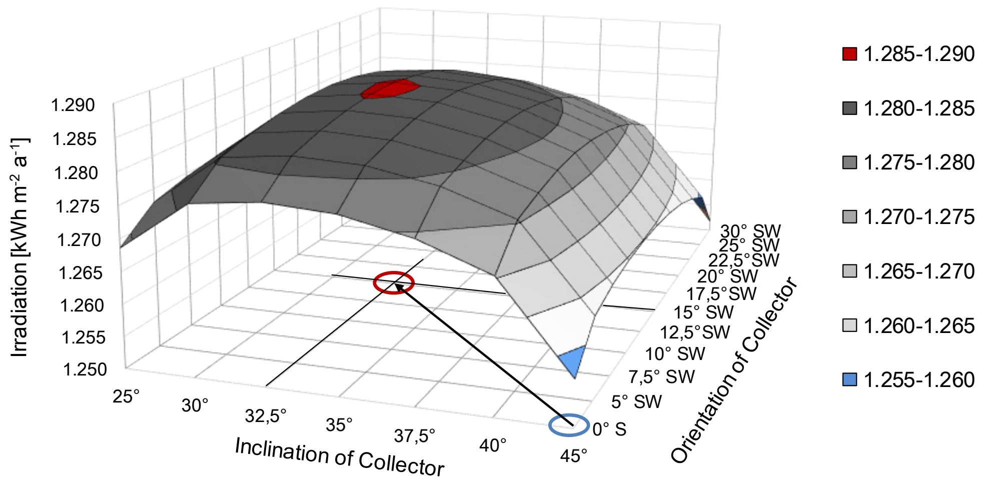


Figure D.4: Definition of maximum irradiation (location: brewery, Ingolstadt)

An orientation of 12.5° southwest and an inclination of 32.5° are favourable parameter for location dairy (Mertingen, Germany). Consequently, the results are comparable to the brewery location. Integrated in the system configuration ID ac+cc-st, the divergence of annual energy supply from collector to basis configuration is 0.1%.

The findings show generally a limited influence for an inclination between 30° and 60° combined with an orientation between 0° and 15° south-southwest of the collector. Main reason are seasonal independent and large energy demands of the analysed systems. A time-related orientation of collectors, e.g. for a main energy demand in summer, provides no advantageous and is not expedient. However, the analysed flat roofs of the companies enable the technical feasibility of inclination and orientation defined above.

Variation of collector design

The variation of the collector design is with a standard (commercial) vacuum tube collector (ITW, 2006). From a technical point of view, flat plate collectors are exchangeable with this collector type. The advantages result from the vacuum insulation:

- better performance with cold weather,
- higher collector efficiency at high operation temperatures,

- higher supply temperature.

The evaluation is on basis of additional energy yield with the SPH-system. Table D.2 illustrates the simulation results for example system configurations. All systems supply more solar process heat to process than with flat plate collectors. It is in a range of 9% (brewery ID solar bw) to 35.9% (dairy ID ac+cc-st) and confirms certain energetic advantages of vacuum tube collector.

Table D.2: System comparison with flat plate and vacuum tube collectors

System configuration	**Energy to Process** Flat Plate [$MWh_{th}\ a^{-1}$]	**Energy to Process** Vacuum Tube [$MWh_{th}\ a^{-1}$]	**Additional Energy to Process** [%]
Brewery ID solar bw	645.1	703.4	9.0
Brewery ID solar bw +hr	503,2	553,6	10.0
Dairy ID ac+cc-st	450.0	611.4	35.9

Reason for that additional energy to process is the higher supply temperatures of the SPH-system. Figure D.5 compares therefore the storage temperature at the top position. It shows a continuous advantage of the SPH-system with vacuum tube collector.

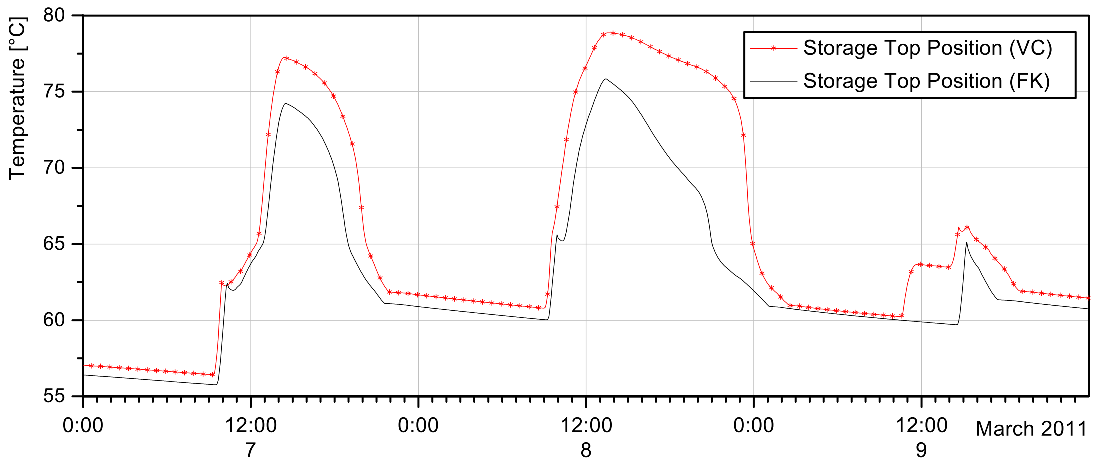


Figure D.5: Storage temperature at top position for FK and VC (ID ac+cc-st)

Figure D.6 compares furthermore the flow temperature of the LGH network at solar process heat supply for the system configuration ID ac+cc-st with vacuum tube collectors (VC) and flat plate collectors (FC).

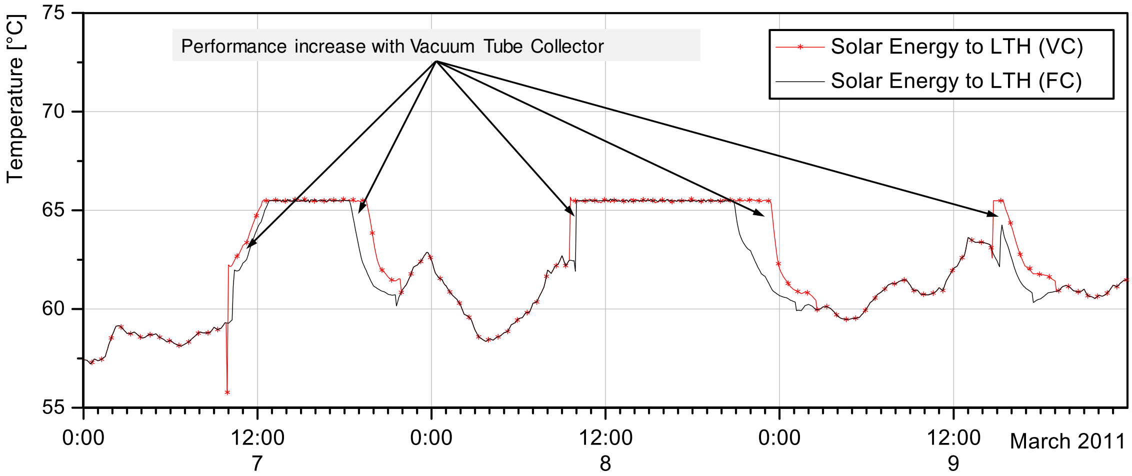


Figure D.6: Flow temperature of LGH-network after SPH-supply

Higher temperatures enlarges operation time of the SPH-system and increases energy supply. This becomes particularly obvious for system with general high temperature levels, e.g. configuration bottle cleaning or configuration ID ac+cc-st (Table D.2). This effect is less clear, for systems with good conditions for solar process heat supply, e.g. configuration ID solar bw and ID solar bw + hr (Table D.2).

Variation of fluid volume flow

The volume flow rate of the collector circuit and connected storage circuit is varied each with the same factor. The variation is with a step size of 0.1 beginning at the basis configuration of 25 l m^{-2}_{ca} for the collector circuit and 23 l m^{-2}_{ca} for the storage charging circuit. The results (Figure D.7) show only minor optimisation potentials.

The system configuration ‘solar bw’ has a maximum at the basis parameter 1.0 and provides no optimisation potential. A small optimisation potential occurs for the configuration ‘ID ac+cc-st’ at a factor of 1.5. This is a result of minimal better collector performance and negligible higher storage temperatures. The energetic improvement is therefore just an enhancement of the specific collector earnings by 2.5 kWh_{th} m^{-2} a^{-1}. That higher volume flow again requires more propulsion energy for pumps and larger pipe diameter. Changing the volume flow is technical feasible but not required.

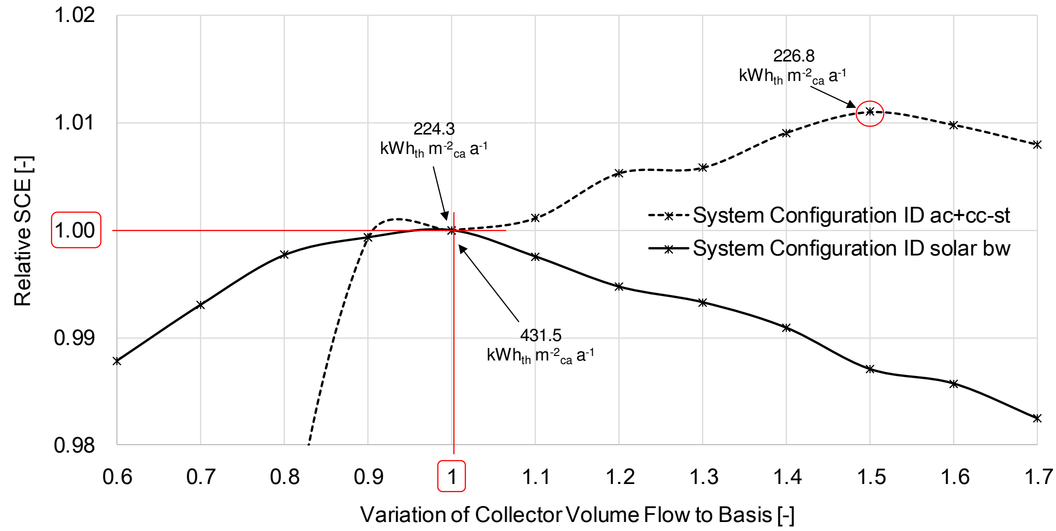


Figure D.7: Variation of collector volume flow

Variation of storage volume

Bollin (2013) describes a connection of storage volume and collector area. According to those findings, 80 l m^{-2}_{ca} is the defined storage volume for the basis system configurations. The variation of the specific storage volume is with a factor of 0.05 from 56–112 l m^{-2}_{ca}. As Figure D.8 illustrates, the configurations ID solar bw and ID ac+cc-st show similar results compared to the efficiency curve of Bollin (2013). The curve of ID solar bw is almost identical contrary to the slightly steeper curve of ID ac+cc-st.

The system configuration ID ac+cc-st requires 30% more storage volume (104 l m^{-2}_{ca}) to reach 3% more specific collector earnings. This is an enhancement form 224.3 kWh_{th} m^{-2}_{ca} to the maximum at 230.0 kWh_{th} m^{-2}_{ca} (Figure D.8). The optimisation with the configuration ID solar bw – as system with high specific collector earnings – is even lower. Significant improvements are not able with enlarging the storage volume.

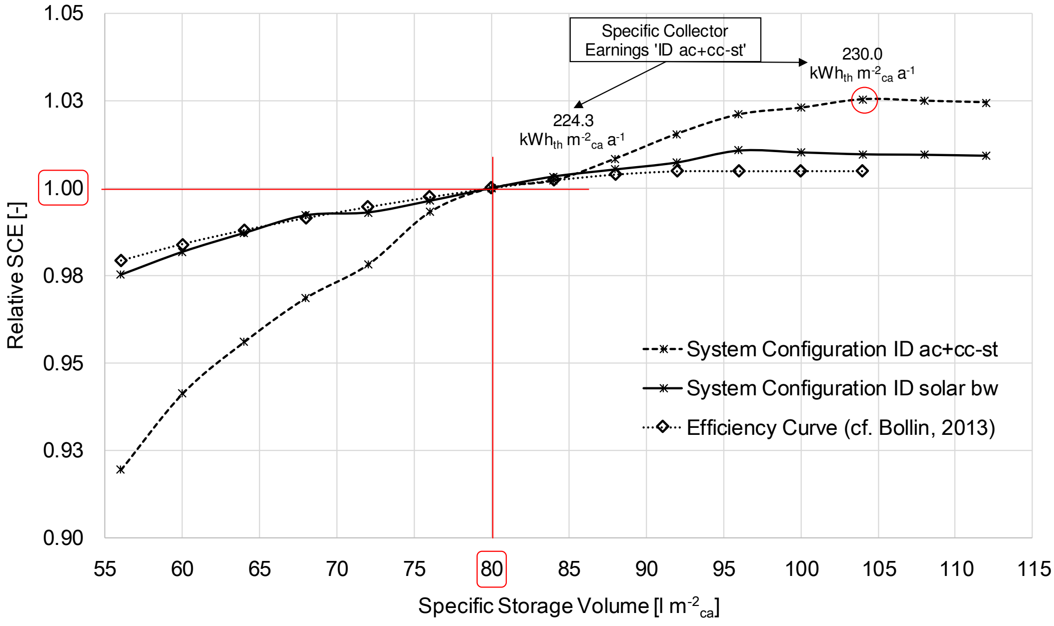


Figure D.8: Variation of specific storage volume

Variation of storage charging and storage discharging

Objective is a favourable temperature stratification of the storage medium with maximum temperature at the top and minimum temperature at the bottom. Hence, stratified charging technology promises advantageous characteristics and is component of all basic system configurations. The variation in this case is with a pipe connection, and should validate advantages of stratified charging. Table D.3 compares the charging technology with the energy to process for exemplary system configurations. Stratified charging provides about 2.5% more energy to process than the systems with pipe connection.

Table D.3: Energetic comparison of different storage charging technologies

System configuration		Stratified Charging [MWh_{th} a^{-1}]	Pipe Connection [MWh_{th} a^{-1}]
Brewery bottle cleaning	Energy to Process	119.0	114.4
Brewery ID solar bw	Energy to Process	645.6	630.4
Dairy ID ac+cc-st	Energy to Process	450.0	440.5

Reason for the better performance of the stratified charging storage is the more favourable temperature stratification. Figure D.9 and Figure D.10 illustrate the difference of stratification between the two technologies for the configuration ID solar bw and ID ac+cc-st.

The storage temperatures with stratified charging are mainly higher at the top position while they are mainly lower at the bottom position. This leads to higher supply temperature to the process on the one side and to lower return temperature to the collector circuit compared to the storage with pipe connection.

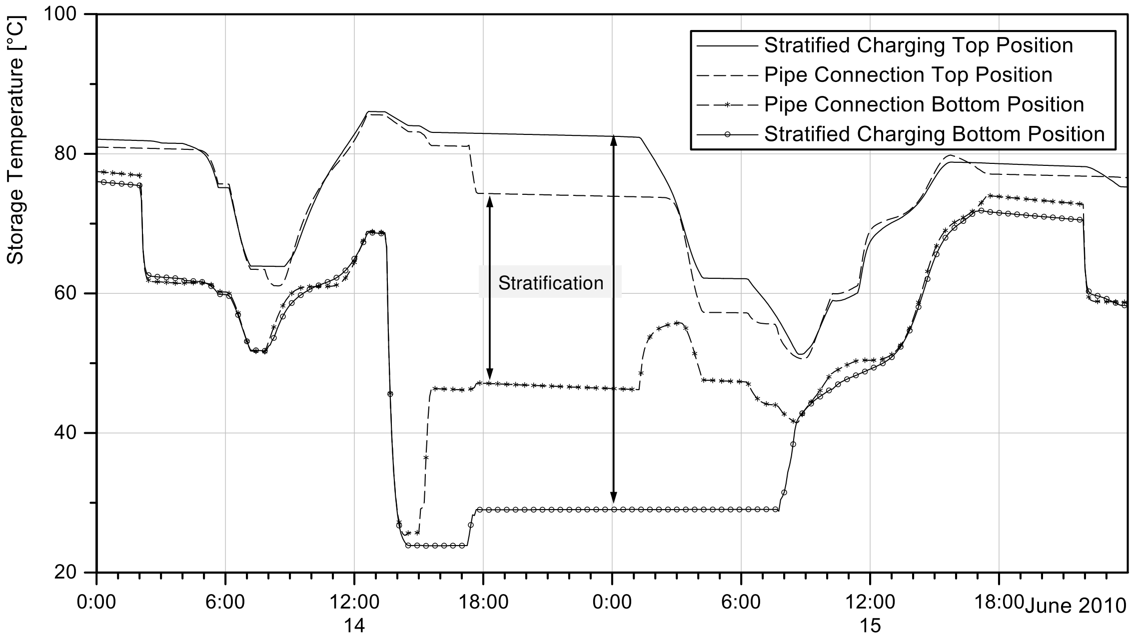


Figure D.9: Stratification of storage with system configuration ID solar bw

The stratification is clearer for systems with low return temperature to the storage as it is for the system configuration ID solar bw (Figure D.9). Figure D.10 compares pipe connection with stratified charging for the system configuration ID ac+cc-st. The stratification in this case is less clear but also present and is a result of the high return temperature to the storage for this configuration.

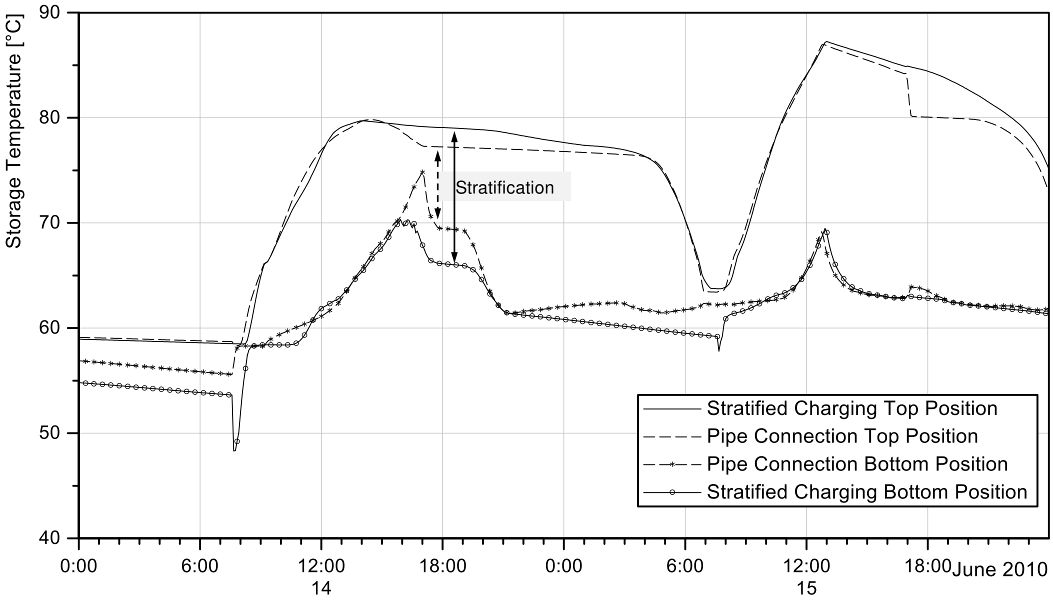


Figure D.10: Stratification of Storage with System Configuration ID ac+cc-st

From a technical point of view is the stratified charging technology feasible. The use of existing storages however, requires something more extensive reconfigurations.

Variation of storage insulation

Minimising energy losses from storage requires an adequate insulation. The storages of the defined system configurations are equipped with a standard (market available) insulation. It is comparable to the insulation of the available storages at the brewery and the dairy and corresponds to a heat loss coefficient of 1.2 W m^{-2} K^{-1}. A stepwise upgrade aims to reduce storage losses and in the same way to increase specific collector earnings. The storage utilization factor uf_{stor} shows first the connection between useful energy from storage and energy loss from storage.

Figure D.11 distinguishes the storage of the configuration ID ac+cc-st and of the configuration ID solar bw. First, there is a large difference of energy loss from storage between the two systems. This is 39.2 MWh_{th} a^{-1} for ID solar bw and 111.3 MWh_{th} a^{-1} for ID ac-cc+st at the basis configuration. In addition to the fact of a higher average temperature of 22 K for the storage in configuration

ID ac-cc+st, describes Table D.4 the further reasons. These differences of storage parameter and location allow just an individual analysis of each storage.

Table D.4: Distinction of storage facts

		Configuration ID solar bw	Configuration ID ac-cc+st
Storage Volume	[m³]	120	160
Storage Surface	[m²]	145	186
location		inside	outside

Reducing energy losses from storage by one third requires an upgrade of the storage insulation to a heat loss coefficient of 0.8 W m^{-2} K^{-1}. Figure D.11 describes this with the storages of the two system configurations. Energy losses decrease from 39.2 MWh_{th} a^{-1} to 26.5 MWh_{th} a^{-1} for ID solar bw and from 111.3 MWh_{th} a^{-1} to 77.8 MWh_{th} a^{-1} for ID ac-cc+st. This effects also the specific collector earnings. Figure D.12 confirms an increase of 4.7% for the configuration ID ac-cc+st and 1.1% for the configuration ID solar bw.

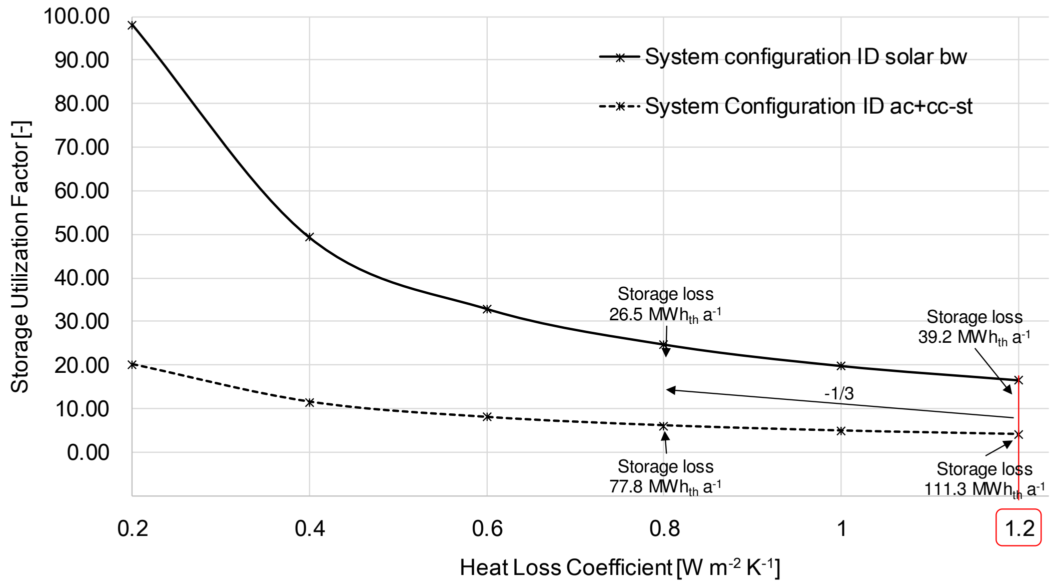


Figure D.11: Comparison of storage utilization factor

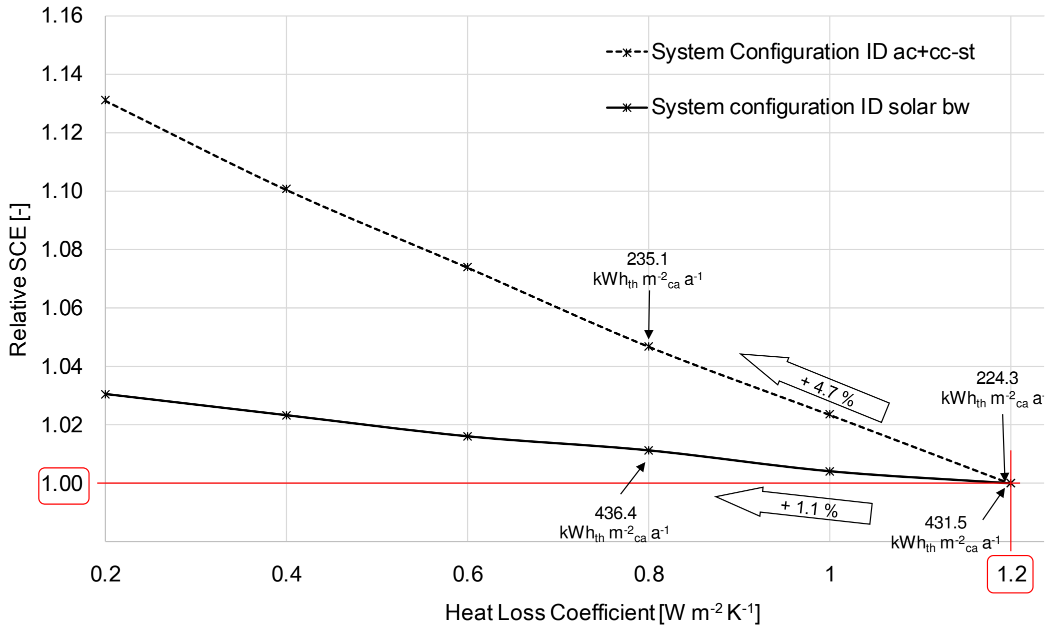


Figure D.12: Variation of storage insulation

An upgrade of the storage insulation to the defined heat loss coefficient of 0.8 W m^{-2} K^{-1} is technically feasible with standard insulation material. This means larger insulation thickness or using material with better insulation standard. Unfavourable conditions with storage location and higher average storage temperature result in a more significant improvement for the configuration 'ID ac-cc+st'. This recommends an upgrade of insulation contrary to the configuration 'solar bw' where the improvement is low with just 1.1%.

D.2 System optimisation

With the parameter from the sensitivity analysis, the optimisation follows two objectives: This is first the system efficiency with increasing specific collector earnings and second the overall performance with sufficient solar fraction. Table D.5 summarises the optimisation parameter and SCE.

Variation of collector area, collector volume flow and storage volume is with a factor to basis as already used with the sensitivity analysis. The variation of all parameter is against the defined parameter for the basis configurations.

Table D.5: Defined configuration parameter for system optimisation

		ID solar bw		ID ac+cc-st	
Collector area	[-]	1.0 *(SCE 1)*		0.8 *(SCE 1,06)*	
Orientation	[°]	15	*(SCE 1,003)*	12.5	*(SCE 1,01)*
Inclination	[°]	32.5		32.5	
Collector Design	[-]	flat plate *(SCE 1)*		vacuum tube *(SCE 1,3)*	
Collector Volume Flow	[-]	1.0 *(SCE 1)*		1.5 *(SCE 1,01)*	
Storage Charging	[-]	stratified		stratified	
Storage Volume	[-]	1.2 *(SCE 1)*		1.3 *(SCE 1,03)*	
Storage Insulation	[W m^{-2} K^{-1}]	0.8 *(SCE 1,01)*		0.8 *(SCE 1,03)*	

Table D.6 compares the simulation results of the brewery configuration ID solar bw with basis and optimised parameters. Solar energy to process increases by 2.8%. This is an improvement of specific collector earnings from 431.5 to 443.2 kW_{th} $m^{-2}{}_{ca}$ a^{-1} and illustrates the already good conditions of the basic configuration. Hence, the optimisation potential is limited. This additional solar energy to process do not justify the necessary efforts for a reconfiguration. The economic evaluation is therefore with the basis parameters of the system configuration.

Table D.6: Optimisation of configuration ID solar bw (brewery)

Energy Source	Basic	Optimised	Potential
	MWh_{th}	MWh_{th}	%
Solar Energy from *collector area*	702.5	715.6	+ 1.9
Energy losses from *storage and piping*	57.4	52.6	- 8.3
Solar Energy to *Process*	645.1	663.0	+ 2.8

A different situation is with dairy configuration ID ac+cc-st. Simulation and the sensitivity analysis promise high optimisation potentials. Reason is first the substitution of flat plate collectors with vacuum tube collectors and second the reduction of the collector area. Table D.7 shows an increase of 57.9% of specific collector earnings for the optimised configuration in contrast to the basis configuration. Despite of a reduced collector area by a factor of 0.8, the total solar energy to process raises from 449.7 to 571 MWh_{th} a^{-1} and demonstrates the advantage of vacuum tube collectors for systems with high temperature level. However, vacuum tube collector effort higher investment costs and must be considered with the economic efficiency calculation.

Table D.7: Optimisation of configuration ID ac+cc-st (dairy)

Energy Source	**Basic** $kWh_{th}\ m^{-2}_{ca}\ a^{-1}$	**Optimised** $kWh_{th}\ m^{-2}_{ca}\ a^{-1}$	**Potential** %
Solar Energy from *collector area*	304.9	454.9	+ 49.2
Energy losses from *storage and piping*	80.6	100.7	+ 24.9
Solar Energy to *Process*	224.3	354.2	+ 57.9

D.3 Economic feasibility of SPH-systems

The economic evaluation focuses on the solar heat supply system and the validation of the energy costs. Solar energy is just able to substitute another kind of energy and not to substitute the main energy supply technology. Hence, costs for conventional energy are basis for the economic evaluation. Figure D.13 illustrates therefore the trend of industry cost for gas and district heating. Main energy source at the brewery is a gas fired steam boiler. The economic system evaluation is with a defined gas-heating cost (equation (D.2)). Basis therefore is the gas price (BMWi, 2015) and considers an efficiency factor for the steam boiler of 85%. The dairy buys its steam energy from a local district heating. The district heating price is basis for the economic system evaluation. Reference for the economic evaluation is 2013.

$$Gas\ Heating\ Costs = \frac{Gas\ Príce}{\eta_{steamboile}} \qquad (\ D.2\ )$$

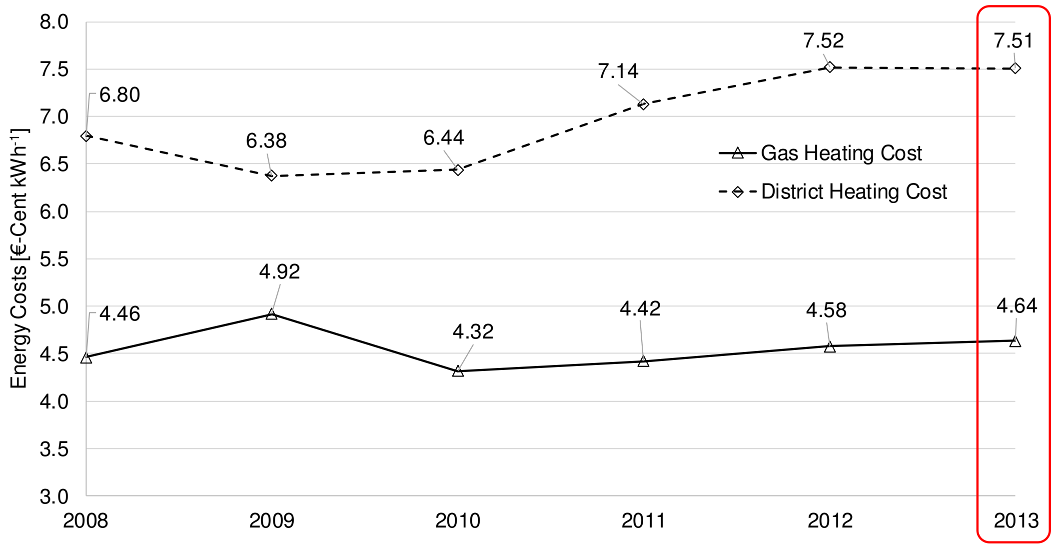


Figure D.13: Industrial energy costs at German industry (BMWi, 2015)

The calculation of costs for the solar process heat is with the annuity method (VDI 2067, 2012). This method separates all accumulated costs on annual basis in four subdivisions:

- Capital-related costs (include investment and planning costs)
- Demand-related costs (include electricity for system pumps)
- Operation-related costs (servicing and inspection)
- Other costs (e. g. insurance; not relevant in this case)

Background are the investment costs. For their determination, comparable large solar-thermal systems provide the input. The research programme SOLARTHERMIE 2000 (2013) gives investment costs of systems installed between 1993 and 2003 with flat plate collectors installed on flat roofs. As system costs raised between 2003 and 2013 (SOLARATLAS, 2013), the calculation considers a cost change of 1.5% a^{-1}. Figure D.14 shows the resulting regression line of the cost analysis.

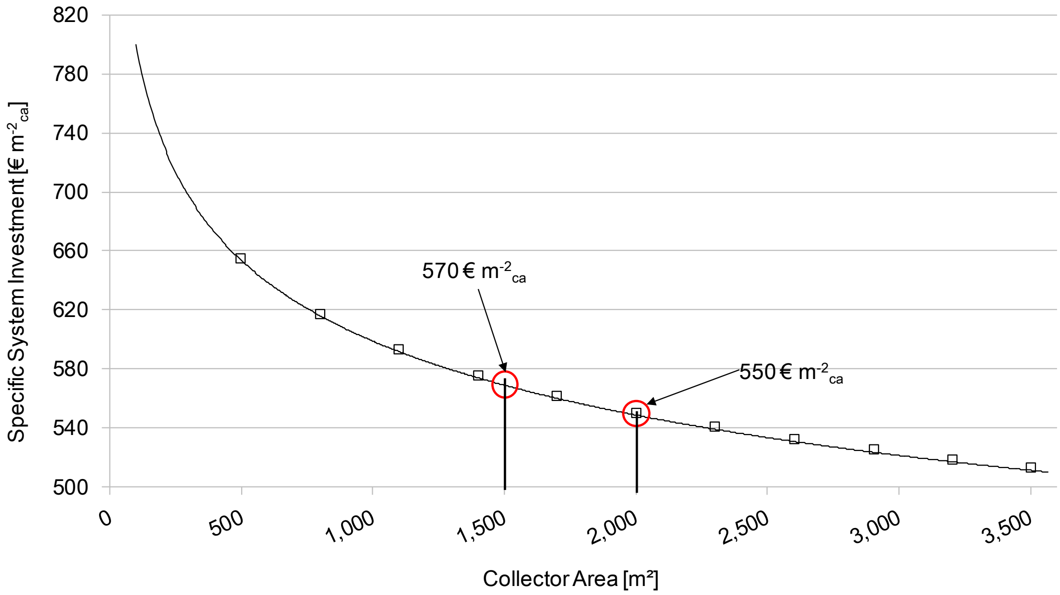


Figure D.14: Specific system costs for large solar-thermal systems (cf. SOLARTHERMIE 2000, 2014, cf. Solaratlas, 2013)

The specific costs (Figure D.14) represent a total investment for all system components. Figure D.15 illustrates therefore a respectively cost structure, what enables considering investment costs of a single component. The storage in this case has a share of 13% of the system costs. Existing storages, as available at the brewery and the dairy, reduce this cost share. For the application to the developed system configurations, 5% is defined as total share on investment.

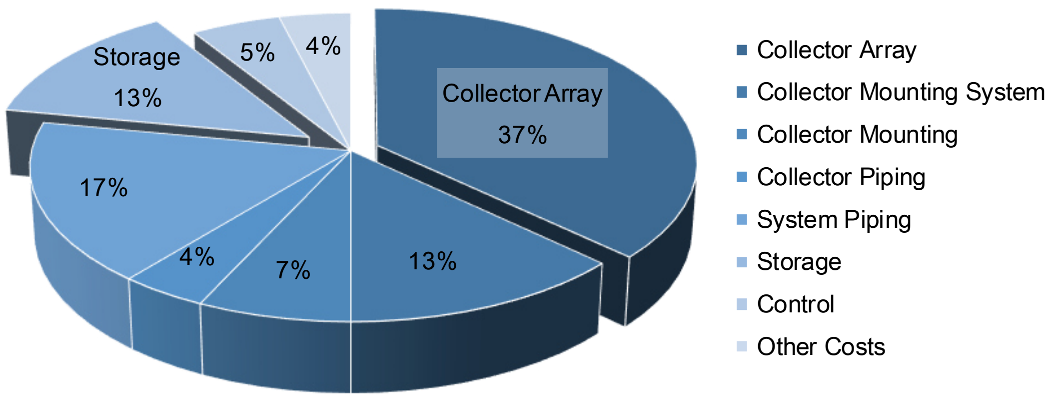


Figure D.15: System Cost Structure (Stryi-Hipp, 2007)

Planning requires an additional charge of 10% based on the investment. The annuity method needs an interest rate what represents on the one side the return on the invested capital or on the other side interests on borrowed capital. Further input are electricity costs (auxiliary power for collector pump) as well as operation related costs (system inspection and servicing). Table D.8 gives the necessary input.

Table D.8: Costs and Cost Factors for System Operation

		Basis
Electricity Price (BMWi, 2015)	0,09 € kWh_{el}^{-1}	---
Pump Energy (BOLLIN, 2013)	3%	Solar Energy from Collector
Servicing (cf. VDI 2067, 2012)	1%	Investment Costs
Inspection (cf. VDI 2067, 2012)	1%	Investment Costs
Interest Rate	4%	---

The Federal Office of Economic Affairs and Export Control gives funding on the investment in SPH-systems (BAFA, 2014). The funding rate depends on an independent expert's opinion and reaches up to 50% of the investment cost. The economic evaluation considers a full funding in each case.

First part of the economic evaluation is for the basis system configurations ID solar bw (brewery) and ID ac+cc-st (dairy). According to Table D.9, the configuration ID solar bw requires with the annuity method 50,955€ and the configuration ID ac+cc-st 64,555€ of annual costs. This is input for the calculation of heating costs of the SPH-system.

Table D.9: Annual costs with annuity method (cf. VDI 2067, 2012)

	ID solar bw (brewery)	**ID ac+cc-st** (dairy)
Capital-related costs	32,000 €	41,400 €
Demand-related costs	1,900 €	1,100 €
Operation-related Costs	17,055 €	22,055 €
Total	50,955 €	64,555 €

Annual costs and the energy to process give the system specific heating costs (equation (D.3). Table D.10 compares these with costs for conventional energy. Heating costs of the basis configuration ID solar bw are about 70% more expensive than gas-heating costs. Even clearer is the result for the basis configuration ID ac+cc-st, where the heating costs are 90% more expensive than the district heating costs.

$$Heating\,Costs = \frac{Total\ Investment}{Energy\,to\ Process} \qquad (D.3)$$

Table D.10: Solar process heat costs compared to conventional heating costs

	ID solar bw (brewery)	**ID ac+cc-st** (dairy)
Energy to Process	645,620 kWh_{th} a^{-1}	449,700 kWh_{th} a^{-1}
Solar-Thermal Process Heat Costs	0.079 € kWh_{th}^{-1}	0.143 € kWh_{th}^{-1}
Gas-Heating Costs	0.046 € kWh_{th}^{-1}	---
District Heating Costs	---	0.075 € kWh_{th}^{-1}

Second part of the economic evaluation is for the optimised systems. Configuration ID solar bw has low optimisation potential. This compared with more investment costs for a larger storage and better insulation do not result in a reduction of solar process heat costs.

Another result is for the optimised configuration ID ac+cc-st. On the one side, a smaller collector area combined with vacuum tube collector supplies clearly more energy to process. On the other side, the investment for vacuum tube collector is about 90% more than for flat plate collectors (Meyer, 2013 and Meyer 2014). The capital-related costs in Table D.11 consider also the larger storage volume and additional insulation with the full share of 13% (Figure D.15). Hence, the annual total costs of the optimised configuration ID ac+cc-st are with 73,130 € about 13% higher than for the basis configuration.

Table D.11: Annual costs with annuity method for configuration ID ac+cc-st (dairy) (cf. VDI 2067, 2012)

	Basis	**Optimised**
Capital-related costs	41,400€	47,890€
Demand-related costs	1,100€	1,560€
Operation-related Costs	22,055€	23,680€
Total	64,555€	73,130€

Despite those higher costs, the higher energy to process of the optimised configuration (Table D.12) leads to lower heating costs. They decrease from

0,143 to 0,108 € kWh_{th}^{-1}. However, the conventional district heating price is with 0,075 € kWh_{th}^{-1} always 30% below the solar process heat costs.

Table D.12: Solar process heat costs on basis of energy to process (ID ac+cc-st)

	Basis	**Optimised**
Energy to Process	449,700 kWh_{th} a^{-1}	675,250 kWh_{th} a^{-1}
Heating Costs	0.143 € kWh_{th}^{-1}	0.108 € kWh_{th}^{-1}
District Heating Price	0.075 € kWh_{th}^{-1}	0.075 € kWh_{th}^{-1}

Energy from solar thermal process heat systems can reach heating costs of 0.079 € kWh_{th}^{-1} as the basis configuration ID solar bw (brewery) shows. This is nearly comparable to the district heating prises, but always clearly above gas heating prices. Taking the long-term view, SPH-systems have the advantage of low demand-related costs and provide therefore a stable development of costs.